2006

Stochastic flow shop scheduling model for the Panama Canal

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by

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A dissertation to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Industrial Engineering

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Iowa State University

Ames, Iowa

2006

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For the Major Program

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ACKNOWLEDGMENTS

When I decided to get a PhD in Industrial Engineering, I began on a long journey and I have many people that have helped me along the way that I would like to thank for their help.

First of all I want to thank God who always has been with me, he has never left me nor forsaken me. He strengthened me when I thought that I could not continue. Thanks be to God who brought the right people and things in the right place and time.

I would like to thank the professors on my Graduate Committee, John K. Jackman , Sigurdur Olafsson, Sarah M. Ryan, William Q. Meeker, Frank Montabon.

I would like to thank my major and co-major professors who encouraged me to complete this research and also answered many of my questions.

I would also like to thank all the professors who taught me during my coursework. They taught me not only their knowledge, but also their attitudes and values.

I would like to thank the members of the Department of Industrial and Manufacturing Engineering Systems, especially Lori Bushore. I remember the first time I came to the Department, Lori was the first person that I met. She saw that I was nervous, but her kindness and smile was a medicine for that. Thank you Lori for all you did for me.

I thank my friends in Panama and the United States. The list is very long and may be takes one hundred pages. God has blessed me with very special people that have taken care,

supported and been prayed for me during this years. I don't have words to tell how grateful I am for them.

I thank the government of the United States through the Fullbright-Laspau Scholarship program and all their members in the Panama United States Embassy, cultural Section. Belsi, Dalys, without your support I could not have completed this.

I would like to give special thanks to the government of Panama through the Senacyt-IFARHU scholarship program for supporting me in my Ph.D. research. I thank Secretary Julio Escobar and Wilson Dawson in IFARHU for their help.

I thank the wonderful people who work in the Panama Canal, especially Juan Wong. Johnny, you had been like a brother. Thank you for the time that you took to meet with me, for directions, for hints, and letters. Thanks so much. I want to thank Jaime Vasquez for the time that you took when I ask you for questions or information. You always answered my requests. Canute Cockburn, Max Newman, Cesar Lopez, Oscar Bazan, Lissette de Arrocha, Arnoldo Cano, Roy Paddy, Abraham Saied, Dorita Pyper, Marcia Ortega, Reinhard Velarde and Desta Greenidge. Thanks so much Desta. Thank you Jorge Quijano, Director of the Marine Operations Bureau and Alberto Aleman Zubieta, the head manager of the Panama Canal for the opportunity to do my research in one of the engineering marvelous of the world..

At last, but not least I want to thank the most important people in my life, my family, my wonderful husband, my extraordinary sons and my mom. Each of one has a story to tell about this adventure and maybe one day we will decide to write it.

ABSTRACT

The Panama Canal can be modeled as a stochastic flexible flow shop for the purpose of scheduling. A metaheuristic stochastic optimization method (Nested Partition) was used to determine if current scheduling practices could be improved by reducing the makespan for vessel traffic. Results indicate that classifying the vessels according to the time that they spend transiting the canal and using some rules and metaheuristic technique for parallel flow shop improves the makespan. The schedules produced by this method show distinct patterns as described by the sequence of vessel types.

1 INTRODUCTION

When the ownership of the Panama Canal was transferred from the United States to Panama in 2000, the Panama Canal Authority (PCA) became responsible for operating a commercially viable enterprise and faced increasing demand for canal transits from the world shipping industry. For 92 years the canal has served as a critical resource for the world maritime shipping trade and has experienced continuous and steady growth, particularly during the last few decades (Vasquez 2003). Increases in containerized shipping (the primary source of canal traffic) since 1960 and travel restrictions that prohibit night transits presents a significant challenge for the PCA: It also presents an opportunity for significant increases in revenue as each containerized cargo vessel represents $90,000 to $150,000 of revenue for one transit. These vessels account for 40% of the total revenue (approximately $500,000,000 per year) for the Panama Canal.

The primary service offered by the Panama Canal is a significantly shorter transit route for vessels between the continents of North and South America. This is achieved using a set of locks that allow vessels to transit the canal. According to the PCA, the daily schedule is the determining factor in achieving a successful canal operation. Not only does the schedule determine the vessel movement, but it also coordinates the actions of all personnel who participate in a transit, including pilots, tugboat personnel, locomotive operators, launch operators, jitney drivers, lock personnel, and linehandlers. Finding the "best" schedule on a daily basis should increase the revenue stream for the PCA.

1.1 Scheduling

Scheduling models for logistic services have been studied in recent years due to the increased importance of this sector of the economy. Service scheduling differs from production scheduling(a context where scheduling has been studied at length). The main differences are: a job is an activity involving a customer, there is no equivalent of inventory, resources are usually more flexible (workforce, rooms, etc.), and the scheduling process tends to be more short term oriented and more reactive (Pinedo 2005).

Differences also exist between real world scheduling problems (like the Panama Canal) and theoretical or mathematical models (Pinedo 1995). Real world scheduling involves dynamic systems and unexpected (seemingly random) events that must be considered when modifying the original schedule. These schedule modifications are considered to be reactive scheduling or part of a rescheduling process.

Numerous stochastic models have been used to schedule real world systems. Gourgand (2003) summarizes the results for different models of stochastic flow shops. A large body of work exists for the classical two-machine stochastic flow shop with relatively little work related to greater than two machines. Typically, these models are used to find the best schedule in terms of the expected value of a performance measure.

Finding the best schedule usually involves some type of optimization of an underlying model. If the fidelity of the model is such that it closely resembles the actual system, then the results of the optimization should produce the intended outcome in terms of the actual performance measure(s). According to April et. al. (2001), real world optimization

problems should be based on simulation models due to the inherent complexities. They also suggest that metaheuristic methods can lead to near optimal solutions while addressing the complexity and uncertainties of these systems. Metaheuristic approaches for simulation-based optimization have been shown to be more efficient and effective than other methods (Olafsson 2005).

1.2 Research Summary

Given that the Panama Canal is a real world system with all the uncertainties and complexities of a stochastic system, a simulation-based optimization approach using a metaheuristic was studied to determine if schedule improvements can be made as measured by the makespan for a set of vessels. Pinedo and Chao (1999), and later Gupta et al.(2000), studied the relationship between makespan and throughput and found that minimizing makespan reduced the idle time in machines and increased the number of jobs per unit time (throughput). For the Panama Canal, a reduced makespan would increase the number of large vessels that could pass through the canal in one day.

Improved scheduling of the Panama Canal operation will have a direct impact on improving cargo transportation in global trade. Expected benefits for the PCA would be increased revenue and better customer service. Scheduling improvements reduce the transit time and costs associated with the utilization of canal resources. The underlying model can provide new insights into scheduling of the Panama Canal operations and stochastic scheduling of flow shops in the context of service industries. This study also provides the

basis for a method that will improve the procedures for scheduling critical operations in the canal and support the decision making process for management operations.

1.3 System Description

The canal (as seen in Figure 1) is 50 miles long running north and south. It consists of a three-step lock waterway connecting the Atlantic and Pacific Oceans across the Isthmus of Panama.

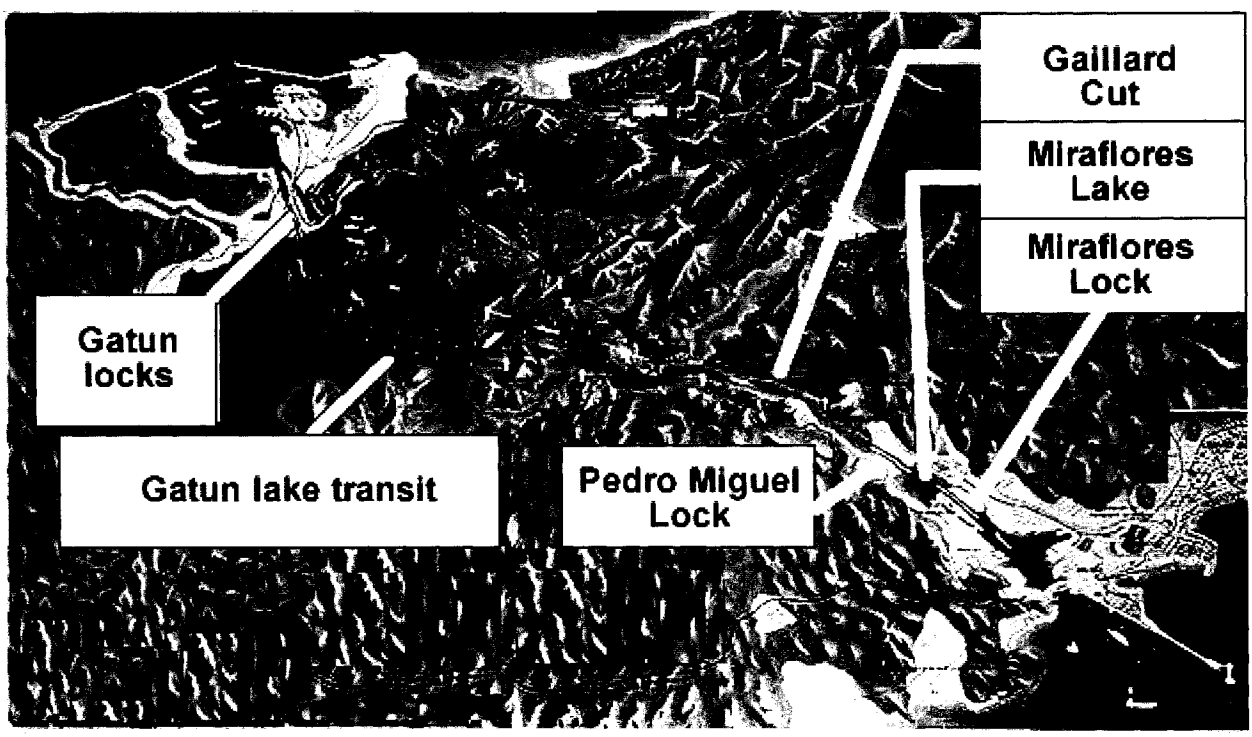


Figure 1 Panama Canal Layout

Traffic in the canal is organized around the schedule of vessels. The schedule for a day describes which vessels will be moving through the Canal, which lane a vessel will use in each lock (east or west), if a vessel has to tie up in the lock because of fog or another

problem, and if two vessels move through the lock together (i.e., tandem transit). Scheduled times for each vessel include arrival and departure times at Miraflores Locks, Pedro Miguel Locks, Gaillard cut, and Gatun Locks.

The capacity of the Canal (in terms of vessels) depends on different factors that are related to the geography, size of the locks [width (106') length (1000') depth (41'-43').], weather, and time of day in the Gaillard Cut and the locks.

Characteristics of system elements that affect the operation of the canal include the following.

1. Vessel
    a. Size - maximum size: beam (106') length (965') draft (39.5').
    b. Load type – standard, dangerous
    c. Speed (knots)
    d. Shape of the vessels
        - Cranes on vessel prevent parallel vessels in the same lock
        - Protuberances
    e. Value – standard, high (submarines with radioactive loads)
    f. Priority - US Navy vessels have priority
    g. First In First Out Rule with the exception of booked vessels
2. Visibility
    a. Light level
    b. Weather: fog, storms

3. Demand is stationary
4. Unbalanced north and south arrivals

1.3.1 Transit Constraints

1. Clear-cut (CC): A vessel because of size, maneuverability, cargo, visibility, or structural peculiarity cannot meet another vessel in the Gaillard Cut.
2. Clear-cut Daylight (CCDL): A vessel cannot meet another vessel in Gaillard cut and must transit Gaillard cut during daylight
3. Daylight lockage: Transit of the locks is restricted to daylight hours.
4. Daylight transit: A transit in which passage through all locks, Miraflores lake, Gaillard Cut, and Gatun lake is restricted to daylight hours. (The period between 20 minutes before sunrise and sunset).

1.3.2 Resource Requirements

Table 1 shows the resource requirements of the vessels during the transit through the canal based on the size of the vessels.

Table 1 Resource Requirements

Resource	Vessel Category	
	Beam < 80'	Beam>91'
Locomotives	4	6-8
Tugboats	3	7-10
Pilots	1	2-3
Linehandlers	13	19-24

The Panama Canal has used a reservation system since 1983 to manage transit openings (slots). There are 23 time slots available each day, 15 for vessels with beam >91' and 8 for smaller vessels. When maintenance is performed on locks, the slots are reduced to 19. The vessels have to reserve an opening one-year in advance. The goal of the reservation system is to improve capacity management through better planning and optimization of canal resources in the daily scheduling of vessels. Vessels with reserved slots have a 98% likelihood to transit in the day chosen and transit within 18 hours is guaranteed or the payment is refunded. This refund represents a penalty function for poor scheduling.

1.3.3 Price Structure

The price for a vessel transit is a fee paid to the Panama Canal. Fees are based on cargo volume and vessel measurements. Fee rates depend on whether a vessel is unloaded or loaded. The Panama Canal applies the Panama Canal Universal Measurement system (PC/UMS) to determine the net Canal tonnage of the vessels (i.e., the vessel size). This system is based on a mathematical formula which calculates the total vessel volume. A net Panama Canal ton is equivalent to one hundred cubic feet of volumetric capacity.

Container vessels have an additional fee for the number of containers on the deck. This is based on another measurement unit, the TEU. This unit is equivalent to a container having length, width and height of 20, 8 and 8.5 feet, respectively. A summary of the fees can be seen in Table 2.

Table 2 Summary of the fees

	DB,T,P6,P8,VC,O,C6,C8	
	Loaded ($/ton)	**Unloaded ($/ton)**
First 10, 000	2.96	2.35
10,001 to 20,000	2.90	2.30
> 20,000	2.85	2.26
	C6,C8 ($/TEU)	
Container	**Loaded**	**Unloaded**
1	49.00	39.20

These prices are fixed and are not connected to the processing time distributions. The processing time distributions can be different for each stage and each type of vessel. These times depend more on the set up time in the locks and the equipment that is used to move a vessel through the locks, as can be seen in Appendix A.

1.3.4 Gatun Locks

The Gatun Locks are the entry point on the Atlantic (north) side of the Panama Canal. The vessel is raised 85 feet using a sequence of three separate chambers. When a vessel enters a chamber, the water level is equalized with the current vessel level. The gates at the entrance to the chamber are opened and the vessel moves into the chamber. The process is repeated until the vessel passes through all chambers. The entire length of Gatun Locks is approximately 1.2 miles. Note that each lock system has two adjacent and parallel lanes (east and west). Vessels are scheduled through either of the two lanes, but the capacity is limited to 1 vessel in each of the three stages.

1.3.5 Gatun Lake

After a southbound vessel clears the Gatun Locks, it enters Gatun Lake and travels 23.5 miles to the north end of Gaillard Cut. The lake covers an area of 163 square miles and can be used as a buffer for storing vessels.

1.3.6 Gaillard Cut

The Gaillard Cut is a narrow channel carved through rocks and gravel for most of its length (8.5 miles). The channel has a minimum width of about 500 feet. This permits unrestricted two-way traffic for about 50% of all vessels using the Canal. For large cargo vessels, traffic is one-way. Presently, the Cut is being widened to accommodate further unrestricted two-way traffic.

1.3.7 Pedro Miguel Locks

Southbound vessels enter Pedro Miguel Locks at the south end of the Gaillard Cut. Here a southbound vessel is lowered 31 feet in one step to Miraflores Lake. The length of Pedro Miguel Locks is approximately 0.83 miles.

1.3.8 Miraflores Lake

Miraflores Lake is an artificial body of water one mile wide that separates the Pedro Miguel and the Miraflores Locks Systems. After clearing the Pedro Miguel Locks, southbound vessels pass through Miraflores Lake to the Miraflores Locks.

1.3.9 Miraflores Locks

Southbound vessels are lowered the remaining 54 feet in two steps to sea level at the Miraflores Locks (slightly over one mile in length). Due to the extreme tidal variations on the Pacific side the miter gates at the Miraflores Locks are the tallest of any in the system. The difference between low and high tide on the Pacific side can be as much as 21 feet (on the Atlantic side the maximum tidal variation is only about 3 feet). Upon clearing the Miraflores Locks, the vessel enters the Pacific Channel and transits for about 3.5 miles to the Pacific Ocean. Note that northbound vessels go through a similar process but in the reverse order.

1.3.10 Resources

1.3.10.1 Pilots

The number of pilots required to transit a vessel depends on vessel dimensions and other vessel characteristics. In addition, the pilot workday cannot exceed the recommended guidelines in place at the Panama Canal. Some vessel transits will exceed these set limits. Hence, for such vessel transits more than one set of pilots may have to be assigned.

1.3.10.2 Linehandlers

Linehandlers board vessels to assist the vessel in the locks by tying and untying locomotive cables, tugboat lines, and vessel hawsers. They also assist vessels during tie up operations at Paraiso and Miraflores tie-up stations.

1.3.10.3 Locomotives

Rail-based vehicles are used to maintain proper vessel positioning in the center of a lock chamber and prevent vessels from colliding with the chamber walls. The locomotives are tied to the vessel by the linehandlers.

1.3.10.4 Tugboats

These watercraft safely guide and properly align vessels on entry to the locks, at tie-up stations, moorings, and through the Gaillard Cut.

1.3.10.5 Miter gates

These gates at each lock separate two water levels. They are closed to allow water equalization between adjacent chambers and are opened after water equalization to allow vessel movements between adjacent chambers.

1.3.10.6 Launches

These small watercrafts transport pilots, linehandlers, and other PCA officials to and from vessels.

1.3.10.7 Culverts

A culvert is a pipe 18 feet in diameter that allows water to be enter into or exit out of the lock chambers for the purpose of equalizing the water levels.

1.4 Current Scheduling Process

Through their agents in Panama, vessels transiting the Panama Canal inform the Panama Canal Authority (ACP in Spanish) of their Estimated Time of Arrival (ETA) and other

information pertinent for transit. A vessel record is subsequently added to the list of vessels to be scheduled for transit. The list of vessels scheduled to transit is manually prepared on a daily basis at Marine Traffic Control (MTC). The Transit Scheduler studies the list of vessels that have declared their readiness to transit during a given day. Based on established procedures, the Transit Scheduler sequences and schedules the vessels for a day.

After the vessel schedule has been developed, this list is passed on to the Pilot Job Software to create the required number of pilot jobs for the day. A pilot job is defined as one contiguous activity in which a pilot engages. Each time a pilot job is created a pilot is assigned to that pilot job. A pilot may perform more than one pilot job during any given day. After the jobs are created, a Transit Operations Officer (TOO) uses the list of available pilots for the day to r assign pilots to these jobs with specified Duty Times. The Pilot's Division of the ACP develops the daily list of available pilots through the Pilot Rotation program maintained. This is a Clipper based computer program that tracks and monitors the available pilot work force and updates their records as these pilots complete assignments, return from vacations, sick leave, etc.

Once a vessel is determined to be seaworthy, the pilot will get the vessel "Underway" to arrive at the vessel's scheduled arrival time to a staging area (buoy 1) near the entrance to the first set of locks.

The following narrative describes the events for a southbound vessel in chronological order. Northbound vessels go through similar events but in the reverse order. As a southbound vessel enters the Atlantic Channel, linehandlers and additional pilots are

transported to the vessel. After the linehandlers board and before the vessel arrives to the Gatun Locks, the necessary number of tugboat(s) approach the vessel and the linehandlers secure tugboat lines to the vessel. As soon as the vessel arrives at the Locks, the linehandlers secure locomotive cables to the vessel from both sides. After the tie-up process, the locomotives guide the vessel into the lower chamber. After the vessel is completely in the lower chamber of the Gatun Locks, the lower miter gates are closed behind the vessel and the water level in the lower is raised to the level of the middle chamber. After water level equalization, the center miter gates are opened and the vessel is guided into the middle chamber. After the vessel is completely within the middle chamber, the center miter gates are closed behind the vessel and the water level in the middle is raised to the level of the upper chamber. After water equalization, the center miter gates are opened and the vessel moves into the upper chamber. Once the vessel is completely within the last chamber, the upper miter gates are closed and the upper chamber water level is raised to the level of Gatun Lake. After water equalization is accomplished, the upper miter gates are opened and the vessel moves out of the chamber and into the Gatun Lake. As the vessel departs the Gatun Locks, the linehandlers will release the locomotive cables at the direction of the pilot on board. The vessel then proceeds through Gatun Lake towards Gaillard Cut. Based on its scheduled arrival time at Pedro Miguel Locks, the vessel may temporarily anchor at Gatun Lake Anchorage or may approach the Cut. The elevation at the Gaillard Cut is 85 feet above sea level.

Assisted by tugboat(s), the vessel enters the Pedro Miguel Locks. The same process is repeated at the Pedro Miguel Locks as at the Gatun Locks, except that there is only one

change in water level. The vessel moves through Miraflores Lake and arrives at Miraflores Locks where similar lock operations are performed

There are two chambers at Miraflores Locks in series. When the vessel clears the locks, the linehandlers leave the vessel. The vessel enters the Pacific Channel on its way to the Pacific Ocean. At this point, the transit of the Panama Canal is officially complete. All pilots except one disembark the vessel after the vessel clears the Miraflores Locks. The last pilot on board disembarks the vessel upon completion of the vessel transit.

At Miraflores and Gatun Locks, vessels may go through one of two types of lockage, namely, regular or relay. At Pedro Miguel only regular lockage is performed. A vessel is said to be engaged in a regular lockage if it is assisted throughout its lockage by one set of locomotives. In contrast, during a relay lockage, two sets of locomotives share the responsibility of guiding the vessel during its lockage. One set accompanies the vessel from its arrival to the middle of the locks, and the second set accompanies the vessel during the rest of its lockage. In the meantime, the first set of locomotives return to assist another incoming vessel.

1.5 Research Problem

This research considers the optimization of schedules for an extended stochastic flexible flow shop with a single objective of minimizing the makespan for a set of jobs (i.e., vessels). It takes into account the elements of the system that include some degree of randomness (i.e., they are probabilistic). Mckay et al. (2002) observed that scheduling in practice has received little attention and scheduling researchers need to move from theory to the practice.

Current scheduling practice was compared with a new scheduling method to evaluate the extent to which schedules could be improved. Current scheduling of the system is performed manually. Wu and Li (1995) point out that a manual approach is tedious and inefficient. This research lays the groundwork for an automated system for scheduling the transit of the vessels through the canal.

This method can potentially be extended to other applications in service environments that can be modeled as a stochastic flow shop. It can also provide insights into rescheduling approaches that deal with random disturbances when they occur.

This research differentiates itself from the large body of scheduling research in that it addresses a scheduling problem in stochastic flow shop systems having more than two machines. A metaheuristic approach, as discussed previously has been used successfully in less complex scenarios.

1.5.1 Primary Research Question

If we model the Panama Canal operation as a Stochastic Flow Shop, does a metaheuristic approach to scheduling produce better results in terms of makespan than the current method?

1.5.2 Hypothesis

A metaheuristic approach coupled with a simulation model should result in better performance than those obtained from the dispatching heuristics currently in use. This is based on previous research that has shown that metaheuristics can address the randomness of

real world problems, provide robust solutions, and may guarantee asymptotic convergence to the optimal (Fu 2002; Voss 2001; April et. al. 2001, 2003; Olafsson 2005).

1.5.3 Inference

If the metaheuristic approach results in better performance, then given a set of historical sequences, we should see a statistically significant reduction in the expected makespan over the estimated mean using simulation results for the historical sequence.

2 LITERATURE REVIEW

This chapter reviews relevant literature in the area of theoretical and real world problems, stochastic flow shop scheduling, simulation optimization, metaheuristics techniques, nested partition method and other related issues.

Scheduling is defined as a process that allocates resources (e.g., machines) to tasks over time while optimizing one or more objectives (Pinedo, 1999). This process produces a schedule (a sequence or permutation) of jobs that describes the order in which jobs will be processed. Schedules can be either deterministic or stochastic. Deterministic schedule models assume that all processing times have a known fixed value. Stochastic schedules treat these processing times as random variables and may consider the arrival time of jobs as a random variable. Scheduling models are also categorized according to the resource or machine configuration and can be described as single machine, parallel machine, flow shop, and job shop scenarios. In a flexible flow shop, there are multiple serial stages with a number of identical machines in parallel at each stage. Each job has to be processed on each one of the stages in just one of the parallel machines. Pinedo (1995)

Some scheduling problems can be formulated as linear models and are well suited for linear programming methods. Other problems are NP-hard, posing unique challenges for optimization. Some algorithms that produce feasible solutions close to optimal in a relatively short time have been used successfully (Fu, 2002).

Heuristics that use dispatching rules prioritize the jobs that are waiting for processing on a machine based in the characteristics of the job, the machine or the processing time

(Pinedo and Chao, 1999). They can be classified as static rules (no time dependence) and dynamic rules (time dependent). Some of the common rules are earliest due date (EDD), longest expected processing time(LEPT), shortest expected processing time (SEPT), Johnson's Rule for stochastic systems (SEPT-LEPT) and others. These rules are used to establish the initial schedule in order to optimize it with other heuristics or metaheuristics.

Objective functions used in operations scheduling are based on throughput, makespan, due dates, setup costs, and others, depending on the type of system. The makespan objective is directly related to the throughput objective (Pinedo and Chao, 1999). The makespan is the time required to complete all jobs and is represented by $C_{max.}$ It represents the time when the last job leaves the system. For the Panama Canal, the makespan would correspond to the time that the last vessel leaves the canal, C_n , and is defined as $C_{\max} = \max(C_1, \ldots\ldots, C_{n)}$.

Table 3 lists some of the differences between static or theoretical scheduling and dynamic or real world scheduling as described by Pinedo (1995).

Kamburowski (2000) studied scheduling n jobs on three single machines in a Johnson flow shop to minimize the makespan. He used Talwar's rule - " Schedule jobs in decreasing order of the difference of the expected makespan." The expected makespan decreased when two adjacent jobs in a given sequence were interchanged.

Table 3 Typical characteristics of Theoretical and Real world scheduling

Problem characteristic	Theoretical Models	Real World
Jobs	Fixed set of jobs	Continuously changing set of jobs
Rescheduling	Not considered	Routinely performed
Complexity	Low	High
Job Priority	Priorities are fixed	Priorities are dynamic
Job preemption	Not considered	Routinely performed
Machine availability	Always available	Machines are down at certain times
Objective function	Single	Multiple
Processing time distributions	Special processing time distributions such as exponential are used	Any distribution

Gourgand et al. (2003) used a combination of metaheuristics and a Markovian performance evaluation model for *m* machines. They classified stochastic flow shop models as shown in Table 4.

Table 4 Stochastic flow shop models

Number of machines	Buffer capacity	Processing time distribution function	Objective Function	Reference
2	0	General	$E[C_{max}]$	Jia,1998; Pinedo, 1982
2	Unlimited	Geometric	$E(C_{max})$	Prasad, 1981
2	Unlimited	Exponential	$E(C_{max})$, $E(C_{max})$	Forst, 1981,1983; Bagga, 1977; Cunningham, 1973; Kamburowski, 1999; Ku, 1986; Makino, 1965; Mittal, 1977; Talwar, 1967; Weiss, 1982
2	Unlimited	Erlang	$E(C_{max})$	Forst, 1984
m	0	General	$E(C_{max})$	Bagga, 1970; Foley, 1984; Pinedo 1982
m	Unlimited	General	$E(C_{max})$	Kamborowski, 2000; Makino, 1965, Pinedo, 1982; Talwar, 1967

Pinedo (1982) considered an *m* machine problem models with and without intermediate storage. The processing time of jobs on different machines were independent and identically distributed random variables. He recommended a rule of thumb when trying to minimize the makespan. Schedule jobs with smaller expected processing times and larger variances in the processing times toward the beginning and the end of the sequence, and jobs with longer expected processing times and smaller variances in the middle of the sequence.

There are several researches developed about stochastic flow shop as we have seen but few of them have been applied to real world problems. Pinedo (1982), Kamborowski and others applied Johnson´s rule to optimize stochastic flow shop scheduling with exponential distribution. However, Hopp and Spearman (2000) point out that in real world scenarios, there are usually more than two machines. Furthermore, Johnson's rule with all its variants is not useful in minimizing makespan.

Pinedo (1995) also discusses that it is very difficult to develop a framework for stochastic scheduling problems given that there are a considerable variations to specify due to the distributions of the random variables.

Bridging the gap between the theory and practice is simulation-based optimization. Simulation is the imitation of the operation of a real world process or system over time. Carson and Maria (1997) defines simulation optimization as the process that determine optimal input parameter values from all possibilities without estimate each one with the objective of minimize resources using at the maximum the information achieved in a simulation experiment.

Fu (2002) explains the term simulation as shorthand of discrete-event simulation where the randomness or stochastic nature of the system is embedded. He establishes that the optimization algorithms do not deal effectively with these stochastic characteristics of the systems, however he states that the nested partition method is a promising approach with potential for simulation optimization.

Metaheuristics, according to Voss (2001), can provide the best possible solutions within time limits. Voss et. al.(1999) define Metaheuristics as "an iterative master process that guides and modifies the operations of subordinate heuristics to efficiently produce high-quality solutions." Metaheuristics is defined by the National Institute of Standards and Technology as an algorithmic framework to solve optimization problems. These algorithms should be adapted with few changes to the characteristics of the system under study.

Blum(2003) presents a survey about metaheuristic and defines it as high level strategies for exploring spaces by using diverse techniques and can be classified in population based and single point search. The single point metaheuristics describe a trajectory in the search process on the other hand the population based metaheuristics describe the evolution of a set of points in the search space.

For stochastic systems a population-based metaheuristic is recommended (Ólafsson 2005). These are evolutionary approaches such as genetic algorithm, nested partitions, or scatter search. Ólafsson (2005) pointed out that genetic algorithm is a robust method and the most popular metaheuristic for simulation optimization, even though there has been little research on convergence of this approach.

The Nested Partition method consists of the following steps:

1. Partition the feasible region into subregions
2. Evaluate the potential of each region
3. Focus on the most promising region
4. Allow backtracking

The effectiveness of the Nested Partition method depends on the best selection of the most promising regions. Ólafsson (2005) describes the importance of accounting for simulation noise when using metaheuristics for combinatorial optimization problems that have stochastic elements. Critical steps in the optimization process include recognizing if a new solution (schedule) is better, deciding if it should be chosen, and recovering from erroneous moves. The computational performance of metaheuristics will be improved if there is a reduction of simulation noise. Another issue discussed by Ólafsson (2005) is convergence analysis. For real world systems, it is better to find a solution within a "□ "of the optimal with some minimum probability.

2.1 Scheduling Rules

Heuristic rules including Johnson's rule, FCFS, maximizing utilization of the Gatun locks (the bottleneck according to PCA), have been used to schedule vessels for transit through the Panama Canal.

2.1.1 Dispatching Rules

SEPT

Prioritize the jobs according to their shortest expected processing time. The short jobs move through the shop more quickly than the long jobs and tend to reduce the blocking. The SEPT sequence is one rule that minimizes expected makespan under certain conditions (Pinedo 1995).

LEPT

Select the job with the longest expected processing time. It is used to balance the workload in parallel machines.

Johnson's rule

Johnson's rule is used to schedule consecutive jobs in a two machine flow shop. It selects the smallest processing time job first for the first machine and the longest processing time job at the second machine.

FCFS

Select the vessel that arrives earliest at the queue (i.e., First Come First Serve). This rule is applied to vessels that have not reserved a schedule slot.

Another rule presented by Pinedo (1995) for flow shops with blocking establishes the sequencing of jobs according to processing time in a SEPT-LEPT order. Vessels are sorted in ascending order and sequenced as 1,3,5…, n...,6,4,2 or 2,4,6,….,n,….,5,3,1. This rule is

optimal for stochastic flow shops with two single machines. Pinedo (1995) points out that problems with more machines are complex and that optimality may not hold for them.

3 MODEL FORMULATION

Based on the structure and behavior of the Panama Canal and the analysis of operation data, the Panama Canal was modeled as a flow shop with stochastic processing times.

3.1 Notation and Decision Variables

3.1.1 Canal

n number of stages in a canal transit

s_k, $k = 1,2,3,\cdots,n$ stage k in a transit direction

r_k, $k = 1,2,3,\cdots,n$ service capacity (parallel service) at stage k

q_k, $k = 1,2,3,\cdots,n$ queue capacity at stage k

3.1.2 Vessels

v_{ij} type of vessel for the jth vessel in vessel set i

N_i total number of vessels in vessel set i

V_i the ith set of vessels, $\{v_{i1}, v_{i2}, v_{i3}, \ldots, v_{iN_i}\}$

T_{km} random variable for the service time at stage k for vessel type m; each T_{km} is assumed to be independent but not identically distributed.

3.1.3 Schedule

□ schedule or sequence of vessels

3.1.4 Performance Measure

$C_{\max}(\theta)$ makespan for schedule □ (time in system for the last vessel in the schedule)

3.1.5 Objective function

Possible objectives for scheduling according to Pinedo (1995) are: maximizing throughput (*TP*), minimizing makespan (C_{max}), minimizing maximum lateness (L_{max}), or minimizing mean tardiness ($\Sigma T_j/N$). These objectives are called regular performance measures. Minimizing the expected makespan was used in this research because it tends to maximize the expected throughput. The objective function is defined as

$$\min E[C_{\max}(\theta)], \tag{1}$$

subject to the constraint that all vessels must appear on the schedule.

3.2 Model description

The two lanes at each lock operate as parallel servers. However, due to the constraints of operating the locks, vessel entry is staggered to allow proper clearances between vessels. Once a vessel enters a multi-chamber lock, it remains in that lane for the entire lock transit. Each job proceeds sequentially through the stages. Figure 2 describes the general flow of vessels through the servers.

The canal system consists of four stages with two sets of parallel machines in stage 1 (representing the two lanes), one set in stage 2, one set of six single server machines in stage 3, and three sets of parallel machines in stage 4. The machines have two lanes, east and west

(except for Stage 3). The flow is in two directions, north and south. The processing times of vessels in each stage are considered to be independent random variables. The buffer between stages 3 and 4 (i.e., Gatun Lake) can be considered to have infinite capacity. Between the other stages there is finite capacity such that blocking can occur. For this research only vessels larger than 91 feet of beam were considered, given that the demand due to these vessels is growing and they must transit in daylight.

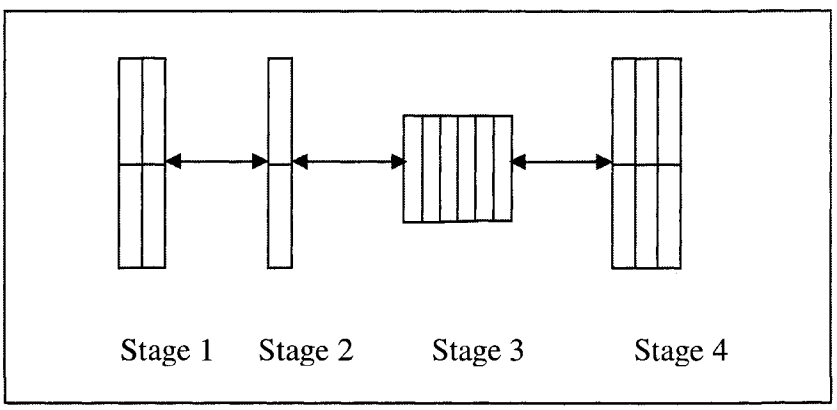


Figure 2 Flow Shop Model of the Panama Canal

Based on Pinedo's notation (1995), this problem may be described as $F4\|C_{\max}$, where, F4 is a scheduling problem type consisting four stages. The objective function in (1) tends to maximize the throughput (*TP*) given the relationship that

$$TP = \frac{n}{C_{\max}}.$$

Analysis of the operation data has shown that the time between vessel arrivals has an exponential distribution, and the processing time in each station has a probability distribution with different means and variance. Each vessel has to transit at each stage in either the east or

west lane, representing parallel machines. Vessels that transit to the north are called northbound and those that transit to the south, are called southbound. The resource availability in the Gatun Locks and Miraflores Lock depends on the direction of travel due to the flow of water. This was not considered in the model.

The number of vessels that can be processed in a given stage depends on the capacity of that stage. Table 5 shows the possible number of vessels for each stage for vessels with beam greater than 91 feet, smaller vessels have different capacity.

Table 5 Resource capacity for each stage

Stage	r_k
1 (MF)	4
2 (PM)	2
3 (Cut)	6
4 (GT)	6

3.2.1 Restrictions

Vessels cannot transit when fog appears, so they have to wait until the fog disappears. Fog occurs in the cut region during the months of May to November. Fog events were not modeled. The model can be extended to incorporate fog occurrences.

3.3 Simulation Model

The simulation model is based on a queueing network for northbound and southbound transits. Figures 3 and 4 show the network of nodes for northbound and southbound transits, respectively. Each node with finite capacity is represented as a queue with one or more servers. A vessel is blocked at a node (i.e., it cannot move to the next node) when the number of vessels present at the next node is $r + q$. If either r or q at the next node has a

value of ∞, then the vessel will never be blocked. If $r = \infty$ and $q = \infty$, then the node represents a simple random variable corresponding to a time delay.

The effect of simultaneous vessel flow in both directions is reflected in the southbound transit model. Vessels moving southbound immediately proceed through the Gatun lock, move across Gatun Lake and wait near the entrance of the Gaillard cut. Once all the northbound vessels have cleared the cut, the southbound vessels may proceed. Given this sequence, the southbound time between the buoy and the entrance to Gaillard cut can be ignored as the vessels are ready to proceed once the northbound vessels have cleared the cut.

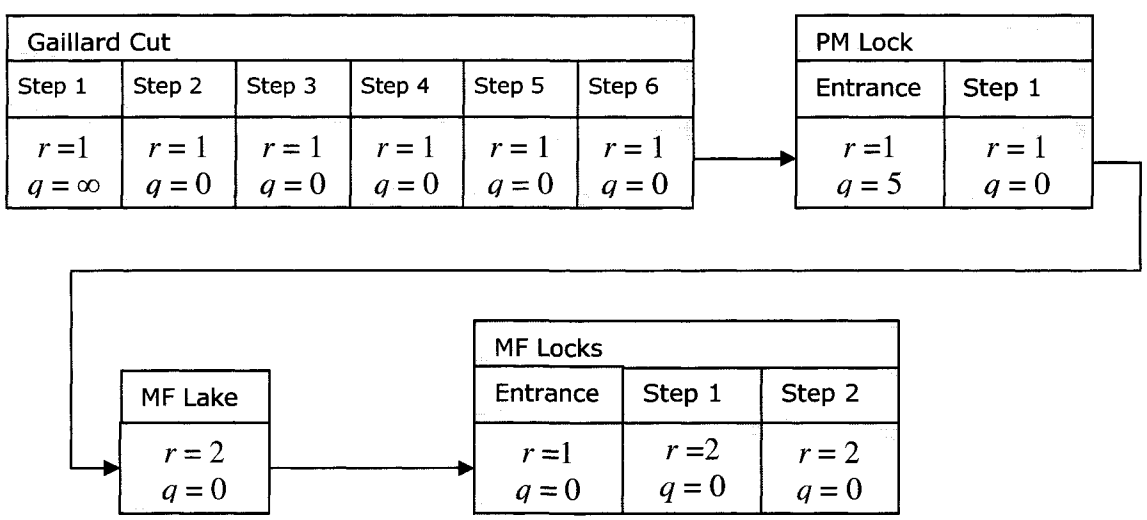


Figure 3 Southbound transit model (*r* is the number of servers; *q* is the queue capacity)

A discrete event simulation model was constructed using four basic events at each node. Given that one simulation run corresponds to a daily schedule, the model was run as a finite horizon system.

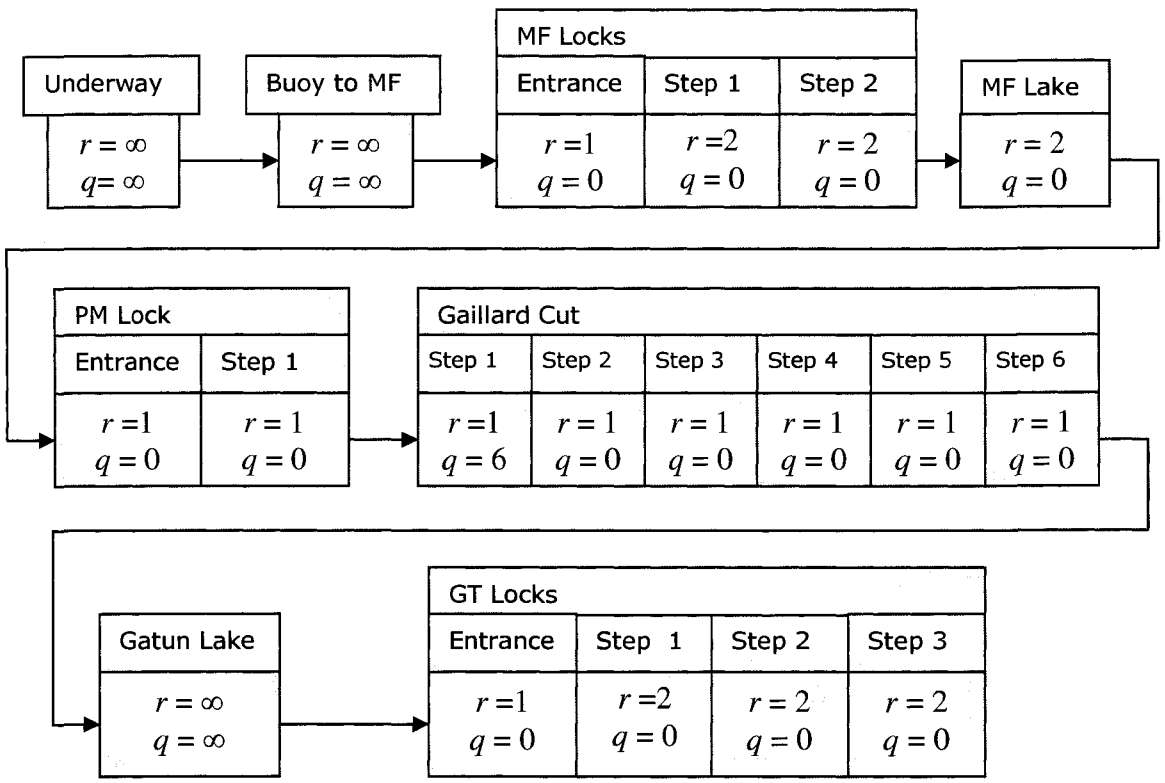


Figure 4 Northbound transit model (*r* is the number of servers; *q* is the queue capacity)

1. Arrival – A vessel arrives at a node. If one of the *r* servers is available, then the Start of Process event occurs. Otherwise, the vessel waits in a queue until a server becomes available.

2. Start of Process - The server becomes busy and the End of Process event is scheduled based on a pseudorandom number generated from a distribution corresponding to the vessel processing time.

3. End of Process – If there is space at the next node, then a Departure event is scheduled and the server is released at the node. Otherwise, the vessel waits in a queue until space becomes available and the server is not released (i.e., the vessel is blocked).

4. Departure – An Arrival event at the next node is scheduled for the vessel departing this node. Next, we check if there is a vessel waiting to be processed at this node. If one is waiting, then the corresponding event is scheduled (End of Process). If a vessel is waiting at the previous node for space at this node (i.e., they were blocked) we check for space and schedule a Departure event for the vessel at the previous node.

The schedule sequence is enforced at the GT, Cut, PM, and MF nodes. The effect of this enforced sequence can be seen when vessel v_{i2} (the second vessel in the schedule sequence) arrives before vessel v_{i1} at MF Locks in Figure 4. Vessel v_{i2} must wait in the queue at the MF Entrance until the first vessel in the schedule arrives.

Assumptions:

- All the vessels can start at the same time. This does not affect the makespan due to the queueing behavior.

- For this study we assume that the processing time in each stage is always relay lockage (i.e., a vessel can be processed in each stage of a multistage lock). In regular

lockage, a vessel must pass through all stages before the next vessel can be processed.

Time distributions

The distributions of the processing times in each stage and the transit time were calculated with JMP software and are shown in Appendix A. A value sampled from the Beta distribution is calculated as $x = \theta + \sigma B$ where B is a random deviate from the beta distribution using the parameters in the tables.

4 METHODOLOGY

A metaheuristic technique was used to find schedules that reduce the mean makespan. This approach is well suited for the dynamic characteristics of real world schedules that are affected by system variables exhibiting stochastic behavior (e.g., vessel arrival, breakdowns, or processing time). The main elements of the new scheduling method for the Panama Canal are as follows.

1. A discrete event simulation model that provides estimates of the makespan based on a set of independent replications.

2. Partition the Panama Canal into four independent stages based on the decomposition method described by Ovacik and Uzsoy (1997).

3. Use the Nested Partition metaheuristic technique proposed by Shi and Ólafsson (1997).

5. Use a modified rule based on the Longest Expected Processing Time (LEPT) at PM Locks for southbound transits to determine the initial most promising region. The modified rule places the next shortest processing time at PM after dry bulk or tanker vessels at the front of the sequence. For northbound transits, Shortest Expected Processing Time (SEPT) at Gatun Lake was used to determine the initial most promising region.. These rules were identified through a set of experiments using the simulation model and will be described in a later section.

4.1 Stage-based Decomposition Method

Stage-based decomposition has been used widely for real world scheduling problems (Ovacik and Uzsoy 1997). A Flow Shop is decomposed by identifying stages that operate asynchronously (or nearly asynchronously). Each stage is treated as a separate parallel or single machine problem and the stages are scheduled separately. Decomposition includes the following steps: bottleneck detection, sub-problem formulation, solution of the sub-problems, and solution of the whole problem.

For the Panama Canal problem, the bottleneck was determined by calculating the utilization of each stage. As seen in Table 6, the bottleneck is the PM stage because it is the busiest stage. To solve the sub-problem at the bottleneck, the nested partition method is used to establish the best sequence of the vessels for this stage. Pinedo (2005) points out that in a multiple-machine environment like a flow shop, the job sequence at the bottleneck establishes the performance of the complete system and all the other stages are scheduled after the bottleneck is scheduled. Based on simulation results, using the PM locks as the basis of scheduling worked well for southbound transits but not for northbound transits. Closer examination of northbound transits indicated that the transit time in Gatun Lake played a more important role. Intuitively, one explanation for this is that vessel order can change over the longer transit through Gatun Lake due to different vessel velocities. This is discussed in more detail in the Nested Partition method section.

Table 6 Utilization of Stages in the Panama Canal

	% Utilization			
Transit Direction	**GT**	**PM**	**MF**	**Cut**
Southbound	21.4	**32.2**	20.3	20
Northbound	17	**24.5**	16	14

4.2 Nested Partition Method

This technique is used for global optimization when a problem has a large but finite feasible solution region. It employs a global sampling strategy method that is continuously adapted via a partitioning of the feasible region. Samples are taken from the entire feasible region in each iteration, with emphasis in each iteration given to the part of the feasible region that is considered the most likely to contain the global optimum. Each partition is nested within the previous partition, eventually reducing the most promising region to a singleton. The partitioning method, and a backtracking feature that allows for exploring regions outside the partition, are part of a global search phase. However, local search methods can also be incorporated into the method by using them to help decide which region to partition, and hence where sampling should be concentrated.

The convergence and efficiency of the NP method depends on the way in which partitions are formed. Convergence improves when good solutions are clustered together in the same partition. If this can be achieved, the NP method rapidly concentrates the search in that partition and converges quickly. This method is simple, robust, and converges to the global optimum of an optimization problem with a finite feasible region. (Shi and Ólafsson 2000).

We now summarize some of the major features of the NP method.

- Few assumptions are made about the structure of the problem. The partitioning strategy implicitly imposes a structure on the problem.
- An initial solution is not needed, as the method takes a global perspective in every iteration.
- The method can incorporate local search methods and hence provides a framework for combining global and local search.
- Bounds on the expected number of iterations needed for convergence can be calculated.

The Nested Partition method is one metaheuristic approach that has been used in NP-Hard scheduling problems. It is readily adapted to simulation models that are used to estimate the objective function. Previous studies have shown that the method converges rapidly for complex problems (Ólafsson 2005, Pichitlamken and Nelson 2002).

4.2.1 Method Description

A set of parameters (i.e., decision variables) $\theta \in \Theta$, where Θ is a feasible region, describes the solution to a problem. An objective function, $L(\theta)$ is identified that can be used to evaluate the "goodness" of θ. The best solution θ^*, is the set of values for θ that produce the best value for $L(\theta)$. When the problem is stochastic (i.e., $L(\theta)$ is a random variable), a point estimate of $E[L(\theta)]$ is used, which we will refer to as $\overline{L}(\theta)$. When a

simulation model is used to find $\bar{L}(\theta)$, replications can be used to determine a confidence interval. In general, if

$$\bar{L}(\theta_1) < \bar{L}(\theta_2),$$

then we would select θ_1 if we want to minimize $L(\theta)$. A conservative test of the difference between $\bar{L}(\theta_1)$ and $\bar{L}(\theta_2)$ is to calculate the 95% confidence interval and check for overlap. If overlap exists, there is no apparent difference between the two means. An alternative approach is to calculate the 95% confidence interval for the difference between the two means, $\bar{L}(\theta_1) - \bar{L}(\theta_2)$. If this confidence interval includes zero, then the two results are not statistically significant. Although, the observed difference between $\bar{L}(\theta_1)$ and $\bar{L}(\theta_2)$ may not be large enough to be statistically significant, the results may still be different. Therefore, in our implementation, we used the mean value as a basis for comparison, because multiple "good" schedules were expected to result from multiple runs of the Nested Partition method.

In the context of scheduling, finding θ^* is a stochastic combinatorial optimization problem that is considered to be NP-hard. The Nested Partitions (NP) method is one metaheuristic that has been used successfully to find near optimal solutions in a reasonable amount of time.

Given a set of n vessels that need to be scheduled, $V = \{v_1, v_2, v_3, \cdots, v_n\}$, there are n! possible schedules (i.e., sequences) that form the solution space Θ. A schedule can be defined as $S = \{s_1, s_2, s_3, \cdots, s_n\}$ where $s_i = v_k,\ s_i \neq s_j\ \forall j \neq i$.

Based on Shi and Ólafsson (2000) the main steps in the method to determine the schedule that produces the minimum makespan is as follows.

1. We initially partition Θ into two subsets, namely, the most promising region and its complement. Let P_0 be the initial most promising region and P_1 its complement.

2. The expected processing time (EPT) at the bottleneck stage is determined for each vessel in V.

3. Sort V based on LEPT in descending order (i.e., highest value first) for southbound schedules and SEPT in ascending order for northbound schedules.

4. Establish a threshold value for LEPT and SEPT to determine the separation point for the two partitions. Calculate the sum of the square differences from the moving average starting with the two highest values and moving down the list for southbound schedules and with the two lowest values for northbound schedules. A large increase in the sum of squares will be identified as the separation point. In the case where no change is seen, the partitions will be equal in size.

5. For northbound schedules, the most promising region is the set of vessel sequences in which the first vessel has the shortest expecting processing time in Gatun Lake. Southbound schedules use a modified rule based on the longest expected processing time at the PM lock. The vessel in the first position is the first vessel after dry bulk and tanker vessel types. If there are x vessels in a partition, then the number of schedules would be $\sum_{i=1}^{x}(n-1)!$ schedules. The complement region would have $n!-\sum_{i=1}^{x}(n-1)!$ schedules.

4.2.1.1 Partitioning Process

Initial partition

Ólafsson and Yang(2005) recommend partitioning the feasible region in such a way that good solutions are grouped together in the same partitions and the poor solutions in another group. In this way, high quality sequences are chosen early in the process. P_0 contains vessel sequences with the LEPT and is considered to be the most promising region. All other sequences belong to the complement region (P_1) as shown in Figure 5.

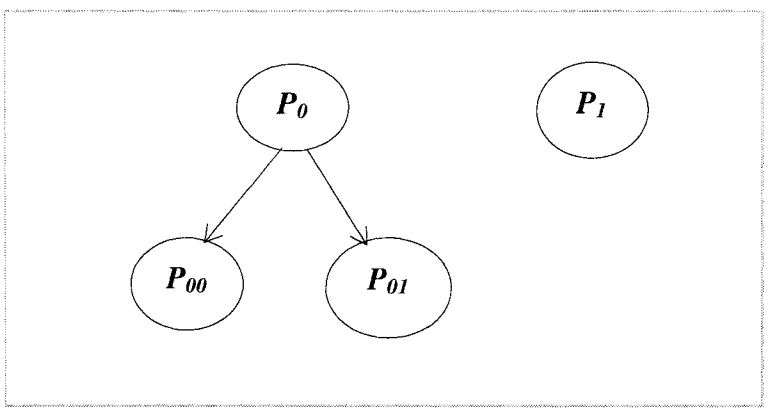


Figure 5 Partition scheme

Schedules are randomly selected from P_0 according to Rinott's two stage ranking and selection procedure (Rinott 1974). The number of schedules, N, to be evaluated is given by

$$N = \left\{ n_0, \frac{h^2 S^2}{\delta^2} \right\}$$

where n_0 is the initial sample size, S^2 is the sample variance estimate of the makespan obtained from the first sample size, h is a constant (based on the minimum probability of correct selection P^* and the number of partitions or regions k), and the initial sample size is

n_0. In this study this value is taken from Table 10.11 in Law and Kelton (2000). For this study we have a value of $k=2$, because we are partitioning in two regions. Ólafsson (2004) stated that the performance of the solution improves with P^* greater than 0.7, so we establish P^* =0.95, and an initial sample size of 40 (which gives us a better estimate of S^2). For these values, the Law and Kelton (2000) table has a value for h of 2.386. δ is the indifference zone and represents the amount by which the difference between the values for two solutions in a region is considered insignificant. This value is subjective and represents an individual's perception of a significant improvement in the objective function. For this study a value of 6 minutes or 0.1 hours.

Using the estimated sample size, simulation with replication is performed for each sample to estimate the mean makespan.

Second Partition

Select the schedule(s), S^*, having the better performance index, in our case, the smallest mean makespan. The partition that contains S^* is the most promising region. If S^* is in P_0, then P_0 is partitioned into P_{00} and P_{01} . All schedules with the first two vessels corresponding to S^* belong to P_{00} and $P_{01} = P_0 - P_{00}$. The sampling procedure and simulation are performed for P_{00}, P_{01}, and P_1.

Third Partition

Again, the partition that contains S^* is the most promising region. The partitioning process is repeated such that schedules with the first three vessels corresponding to S^* are

placed in one partition. If P_{00} is the most promising region, then we create P_{000} and P_{001}. At this point, P_{01} and P_1 are combined for the surrounding region (as shown in Figure 6). At any point in the process, we are sampling from three separate regions. In the next iteration P_{000}, P_{001} and the surrounding region are evaluated. The process is repeated until all vessels are assigned to the schedule.

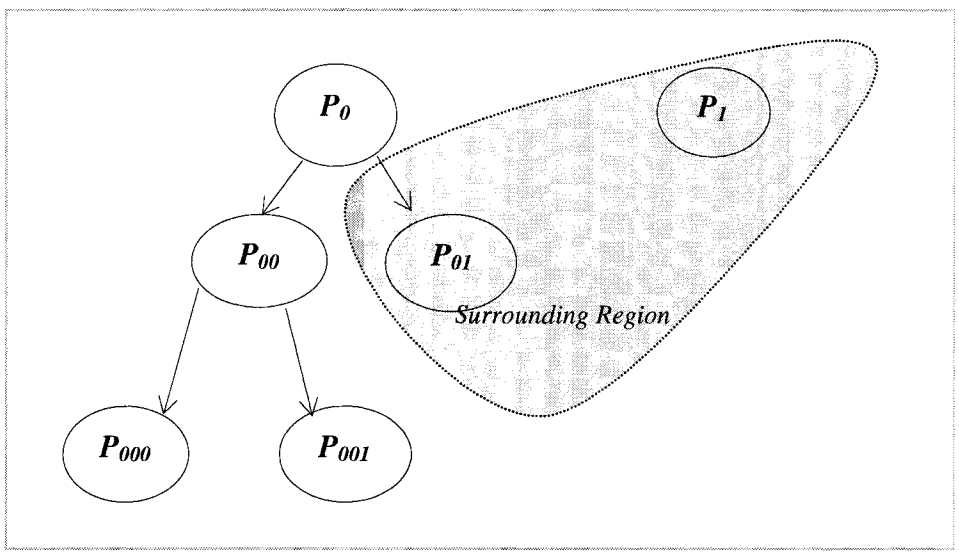


Figure 6 Surrounding region

If the promising region results in a subregion of the original most promising region then we switch to this most promising region. For example, in Figure 6, if $\overline{L}(\theta_{00}) > \overline{L}(\theta_{01})$, then we switch the nodes and assign P_{001} as the most promising region. If there are two most promising region and one is from the original most promising region and the other is from the surrounding region, then chose the original most promising region for the next iteration, if both are from the same most promising region, then broke the tie assigning equal probability to be selected. If it is found that S^* is in the surrounding region, then we

backtrack to the previous most promising region (in this case moving to P_0, the grandparent of P_{00}) as shown in Figure 7. By backtracking, the partitioning process is restarted at the parent node.

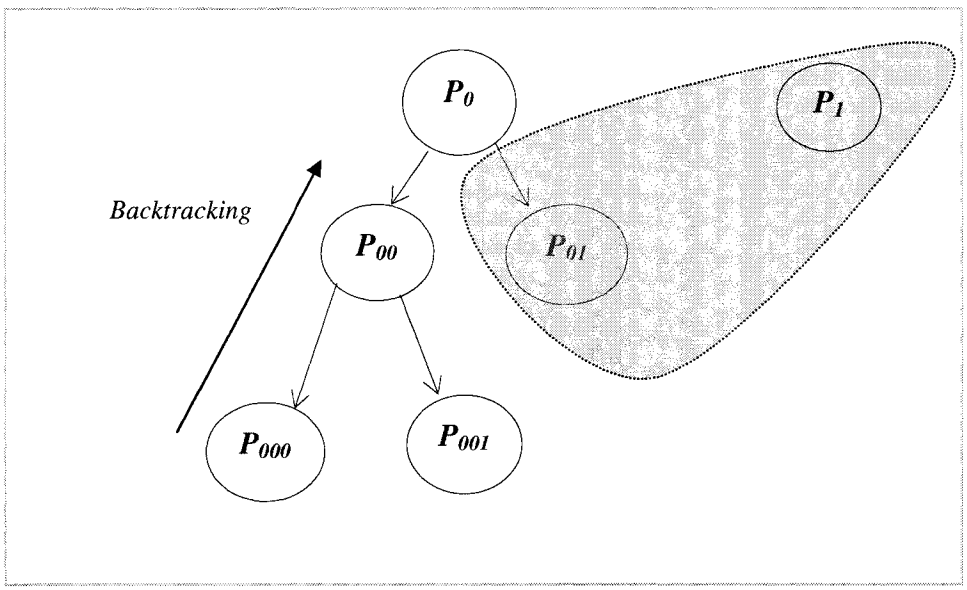


Figure 7 Backtracking

4.2.2 Example

Four vessels have the processing time distributions in the PM stage (the bottleneck) as shown in Table 7.

Table 7 Mean processing times in PM stage

Vessels	Mean processing time (hours)
1	0.76
2	0.74
3	0.61
4	0.56

P_0 contains all sequences in which vessels 1 or 2 appear first, because they have the longest expected processing times. P_1 contains all other sequences, namely, (3,-,-,-) and (4,-,-,-). After sampling from the P_0 and P_1 and running the simulation, we find S^*= {2,1,4,3}. Therefore, the most promising region, P_0, is partitioned into two regions P_{00} and P_{01}. P_{00} contains all sequences {2,-,-,-} and P_{01} contains sequences ({1,-,-,-}. After sampling from the P_{00}, P_{01}, and P_1 and running the simulation, we find S^*= {2,3,1,4}. The most promising region, P_{00}, is partitioned into two regions P_{000} and P_{001}. P_{000} contains all sequences {2,3,-,-} and P_{01} contains sequences {2,1 U 4,-,-}. The process is repeated until all vessels have been assigned.

This problem seems simple as there are only 24 possible permutations. If the number of vessels is 8, then Θ contains 40,320 possible sequences. If this number increases to 13 vessels, the number of different sequences increases to 6,227,020,800. Recall that the average daily demand of vessels in the Panama Canal is 38.

4.2.3 Rules for defining the initial partitions

Experiments were run using the simulation model to evaluate the effectiveness of different rules in selecting vessel sequences for the most promising region (P_0). A total of 40 samples of sequences (20 for northbound and 20 for southbound) were selected at random from different days in the data set using random numbers to pick the dates. The standard deviation of the % difference using the rules was estimated for different sample sizes. A sample size of twenty in both directions was selected based on relatively little change in the standard deviation.

The average makespan was estimated using 200 replications of the simulation. The SEPT-LEPT rule and LEPT rule (at PM) consistently selected a region that was more promising than the actual schedule as shown in Table 8 and Table 9. However, for the northbound transit, the SEPT, LEPT, SEPT-LEPT rules were not consistent. The complete table with the confidence intervals is in Appendices C, D and E.

Table 8 Southbound transits using Pedro Miguel Lock Rules (Set 1)

	Makespan simulation	LEPT	SEPT	S-L1	S-L2	Diff LEPT	Diff SEPT	Diff S-L1	Diff S-L2	# of vessels
1	6.484	6.381	6.444	6.347	6.485	1.589	0.617	2.113	-0.015	8
2	7.567	7.427	7.441	7.408	7.441	1.850	1.665	2.101	1.665	10
3	8.162	7.95	8.052	7.874	7.998	2.597	1.348	3.529	2.009	13
4	6.566	6.38	6.478	6.386	6.494	2.833	1.340	2.741	1.097	8
5	6.364	6.151	6.268	6.092	6.19	3.347	1.508	4.274	2.734	8
6	7.886	7.61	7.7	7.697	7.78	3.500	2.359	2.397	1.344	11
7	5.688	5.394	5.514	5.387	5.512	5.169	3.059	5.292	3.094	5
8	8.035	7.895	7.966	7.882	8.028	1.742	0.859	1.904	0.087	12
9	7.695	7.49	7.601	7.538	7.707	2.664	1.222	2.040	-0.156	11
10	7.22	6.987	7.071	6.915	7.024	3.227	2.064	4.224	2.715	10

Table 9 Southbound transits using Pedro Miguel Lock Rules (Set 2)

	Makespan simulation	LEPT	SEPT	SEPT-LEPT1	SEPT-LEPT2	Difference LEPT	Difference SEPT	DIFF S-L 1	DIFF S-L 2	# of vessels
1	6.297	6.284	6.325	6.275	6.314	0.21	-0.44	0.35	-0.27	8
2	7.512	7.43	7.51	7.44	7.528	1.09	0.03	0.96	-0.21	11
3	6.382	6.231	6.273	6.234	6.264	2.37	1.71	2.32	1.85	8
4	6.933	6.869	6.93	6.882	6.971	0.92	0.04	0.74	-0.55	9
5	7.916	7.704	8.2	7.716	7.795	2.68	-3.59	2.53	1.53	12
6	6.771	6.683	6.749	6.688	6.762	1.30	0.32	1.23	0.13	9
7	7.862	7.647	7.713	7.644	7.799	2.73	1.90	2.77	0.80	11
8	7.672	7.701	7.729	7.694	7.729	-0.38	-0.74	-0.29	-0.74	11
9	7.175	7.169	7.266	7.231	7.323	0.08	-1.27	-0.78	-2.06	10
10	8.716	8.353	8.524	8.304	8.442	4.16	2.20	4.73	3.14	14

In order to decide which rule should be used to define P_0 for southbound transits, some experiments were run in which the vessel sequence was changed. It was found that when dry bulk or tanker vessels were in the sequence, they would appear first based on LEPT at PM. However, the Nested Partition method would find the best result in P_1 . It was found that when a vessel after dry bulk and tanker vessels (which were at the front of the LEPT sequence) was moved to the front of the LEPT sequence, then P_0 behaved well as the most promising region.

The northbound sequences were analyzed to compare the processing times in each stage. It was found (by examining the simulated transit times) that the critical stage for northbound transits was Gatun Lake, even though it is modeled as an infinite capacity region. Vessels that were slower in this stage would cause delays for the other vessels behind it in the sequence at the Gatun lock. This suggests that different sequences may be necessary at different stages. The simulation was performed again using the SEPT and LEPT for Gatun Lake to sort the sequences for northbound transits. Results obtained with SEPT rule showed more consistent improvement in the mean makespan as can be seen in Table 10.

Table 10 Northbound transits using Gatun Lake Rules (Sample 1)

	Makespan simulation	LEPT	SEPT	S-L1	S-L2	Diff LEPT	Diff SEPT	Diff S-L1	Diff S-L2	# of vessels
1	14.811	14.516	14.231	14.398	14.542	1.992	3.916	2.788	1.816	10
2	14.142	13.886	13.642	13.866	13.705	1.810	3.536	1.952	3.090	8
3	13.679	13.358	13.316	13.385	13.316	2.347	2.654	2.149	2.654	7
4	13.432	13.539	13.362	13.44	13.394	-0.797	0.521	-0.060	0.283	7
5	13.882	13.537	13.455	13.725	13.68	2.485	3.076	1.131	1.455	7
6	14.419	14.566	14.218	14.291	14.326	-1.019	1.394	0.888	0.645	9
7	14.351	14.267	14.028	14.139	14.149	0.585	2.251	1.477	1.408	8
8	14.924	14.853	14.679	14.946	14.78	0.476	1.642	-0.147	0.965	8
9	13.144	13.35	12.853	13.092	13	-1.567	2.214	0.396	1.096	6
10	15.638	15.65	15.438	15.618	15.503	-0.077	1.279	0.128	0.863	13

Table 11 Northbound transits using Gatun Lake Rules (Sample 2)

	Makespan simulation	LEPT	SEPT	SEPT-LEPT1	SEPT-LEPT2	Diff LEPT	Diff SEPT	DIFF S-L 1	DIFF S-L 2	# of vessels
1	14	14.05	13.94	13.95	13.93	-0.41	0.41	0.29	0.44	9
2	13.5	13.6	13.38	13.52	13.63	-0.71	0.89	-0.10	-0.96	8
3	14.3	14.31	14.22	14.3	14.38	-0.03	0.56	0.04	-0.53	10
4	14.93	14.86	14.57	14.71	14.78	0.48	2.41	1.50	1.01	11
5	14.66	14.71	14.62	14.63	14.63	-0.32	0.31	0.23	0.19	11
6	14.42	14.3	14.2	14.28	14.22	0.87	1.53	0.96	1.41	10
7	13.92	13.91	13.79	13.97	14.55	0.04	0.94	-0.37	-4.58	9
8	14.69	14.56	14.41	14.53	14.6	0.89	1.90	1.06	0.60	10
9	15.09	15.06	14.93	15.1	15.15	0.19	1.04	-0.07	-0.40	12
10	14.99	14.87	14.66	14.86	14.81	0.79	2.22	0.85	1.17	11

The confidence intervals for the vessel sequences in the datasets indicate that the rules for the initial most promising region generate vessel sequences that have better or equivalent performance in terms of the makespan.Simulation Model

4.2.4 Verification and Validation

The operational model was compared with the simulation model and the real system by evaluating each stage, time distributions, makespan, and the logic of each event.

The vessels are classified in eight categories according to the market segment: Container 6, Container 8 (bigger), Tankers, Dry Bulk, Vehicle Carriers, Others, Passengers 6, and Passengers 8. Each category has different time distributions in each stage.

To validate the system, the same set of 40 different sequences of vessels (20 northbound and 20 southbound) was used as previously.

In the first step, verification of process times was performed by comparing the 95% confidence interval for the mean processing time at each node of the simulation model with the mean values estimated for the real system. Another important verification step was to check for any switching of sequence order through the four nodes (GT, Cut, PM, and MF). To verify that switching did not occur, vessel sequences were followed through the entire transit.

To check the validity of the model, the actual makespan of the sequences sampled, and the mean makespan of the simulation model were compared to find if there were any discrepancies.

After finding some discrepancies, we traced the sequence of events to locate the source of the deviation. The problems identified were due to distribution parameters.

Some of the values of the simulation makespan are very close to the historical data values and others are shorter. One reason is that the vessels in the canal are released at different times, but in the simulation model all the vessels start the transit at time zero. Another reason is that the historical data has some unexplained delays, which can be treated as anomalies.

4.2.5 Determination of number of replications

The number of simulation replications is an important parameter in this method. It is well known that as the number of replications increases, the width of the confidence interval for a performance measure decreases. For nested partitions, the tradeoff is between the time to perform the simulation and the ability to differentiate between two schedules based on a confidence interval.

The confidence interval for the simulation mean was calculated based is given by

$$\bar{X} \pm t_{n-1,1-\alpha/2}, \left(S/\sqrt{n} \right),$$

where n is the number of replications for the simulation and S is the estimated standard deviation of the replications. A value of 0.05 was selected for □ (i.e., a 95% confidence interval). As the number of replications increases, more is known about the parameters of the population, so the width of the confidence interval narrows.

To select the number of replications, n, we ran each category of vessels for different values of n (as shown in Table 12 and Figure 8). After 200 replications, the change in the confidence interval width is negligible. Therefore, 200 was selected as the number of replications.

Table 12 Number of Replications of a sequence

Sequence Nov2 Southbound

n	LB- CI (Hours)	UB-CI (Hours)	95% CI Width (Hours)
5	14.741	16.272	1.531
10	15.044	16.542	1.498
20	15.172	15.78	0.608
30	15.33	15.897	0.567
40	15.325	15.727	0.402
50	15.436	15.825	0.389
100	15.531	15.716	0.185
200	15.516	15.642	0.126
300	15.512	15.613	0.101
400	15.469	15.564	0.095
500	15.554	15.627	0.073
600	15.513	15.591	0.078
700	15.56	15.622	0.062
800	15.546	15.609	0.063
900	15.546	15.609	0.063
1000	15.549	15.603	0.054

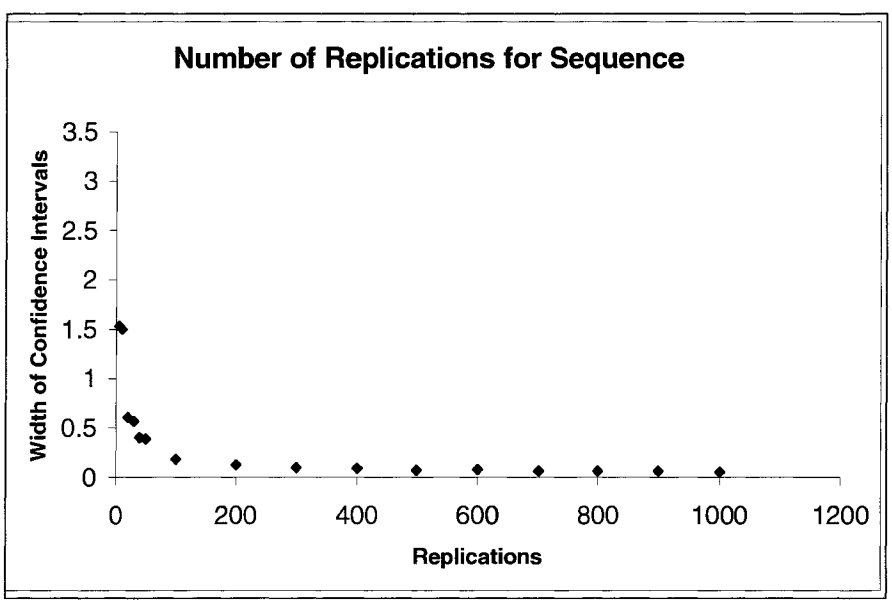


Figure 8 Number of replications

4.3 Stochastic Optimization with Nested Partition

4.3.1 Verification of Sample Size

To verify the sample size for Nested Partition, four sequences (two from northbound and two for southbound) were selected. The sequences were run for minimum sample size of 2, 5, 10 and 20. The expected makespan and the confidence intervals in each run were estimated and can be found in Appendix .... It seems that increasing the number of samples for the nested partition method beyond 2 does not make any significant improvement in the performance measure.

4.3.2 Partition sampling

Starting with P_0 and P_1, random sampling of vessel sequences is performed to start the process and partition this region according to the objective function in (1). The first position in the schedule is assigned based on the most promising region, P_{00} . Sampling is performed on P_{00} and P_{01} and the surrounding region, P_1. The second position in the schedule is assigned based on the most promising region and the process is repeated until all vessels have been assigned. This process is illustrated by the example in Figure 9. If a sample in the surrounding region has a lower value for the makespan, then the algorithm backtracks to the prior most promising region (i.e., the parent node) and the process begins again from this node. If the best solution is found in the complement region of the most promising region, the algorithm switches these regions (i.e., the right child of the parent becomes the left child) and continues the process.

4.3.3 Verification of Partitioning Process

Two samples with 20 sequences each one were used to verify the optimization model with 200 simulation replications for each schedule sample and a minimum sample size of 2 schedules. Each step of the nested partition method was evaluated according to the algorithm to check the logic during the process. The initial sample, the partitions, the regions, and the surrounding regions were compared with the manual diagram of the sequences.

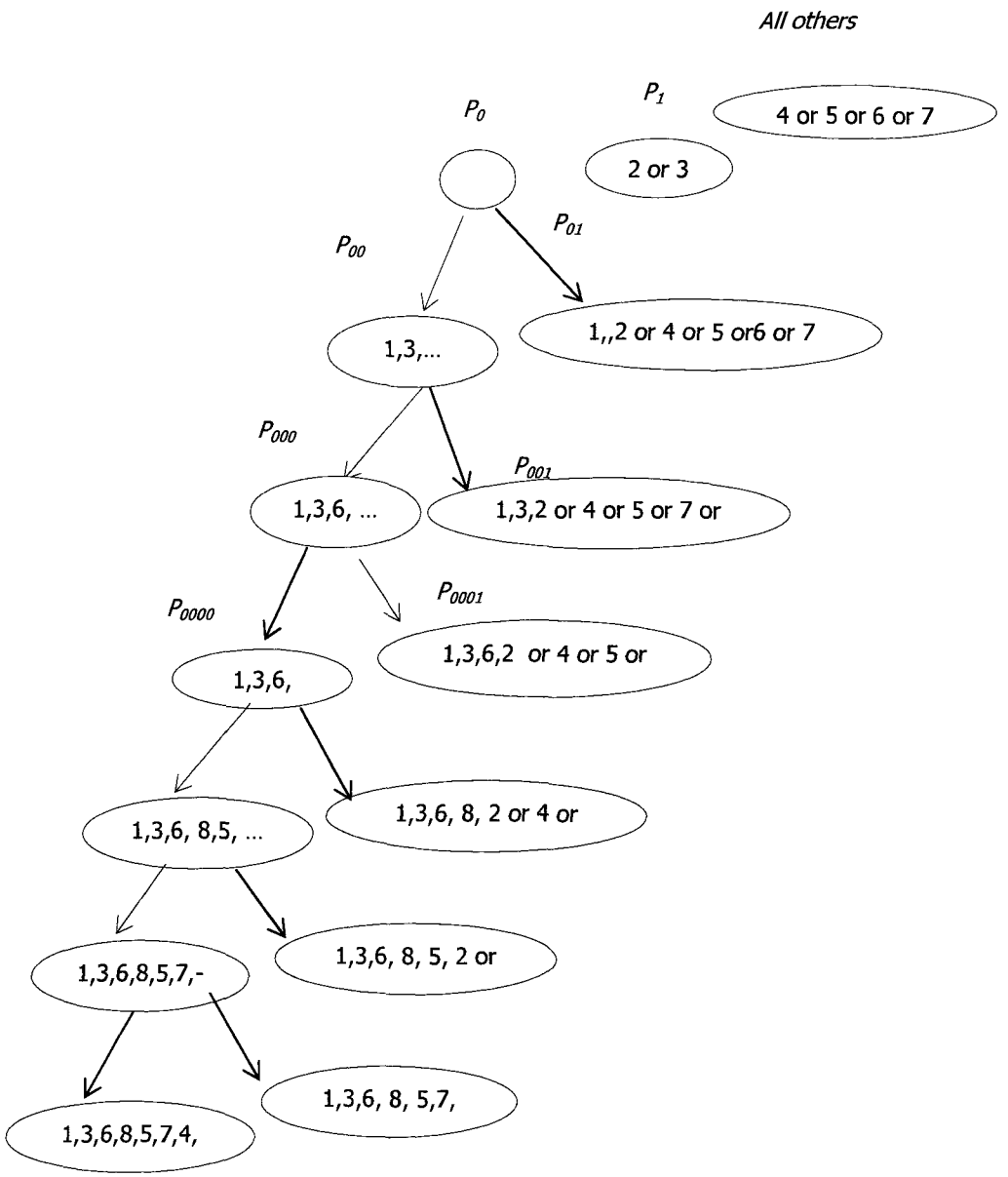


Figure 9 Partition verification. Northbound Direction. Feb. 19 2003 Sample #2 Sequence#2 (C6,C6,C8,DB,O,O,VC,VC) - 1,2,3,4,5,6,7,8

5 RESULTS

Simulation tests were performed to evaluate the improvement in mean makespan of 40 schedules (20 northbound and 20 southbound) that were generated by the Nested Partition Method.

Due to the characteristics of the system. the Nested Partition method produces multiple "good" schedules for each of the 40 sequences. For the purpose of comparing with the original schedule, one of these schedules was selected.

As can be seen in Table 13, northbound schedules obtained by the Nested Partition method appear to follow the same pattern in the beginning and the end of the sequence. C6, C8 and P6 are in the beginning of the sequences and VC and DB at the end. It suggests that the initial and the end positions are critical factors in a schedule. It is also clear that the historical data does not conform to this pattern.

Figures 10, 11 and 12 shows the time at which vessels left a location for sequence 1. The historical data in Figure 10 is one observation. The simulated and nested partition plots in Figures 11 and 12 are based on the average of 200 replications. The sequence obtained when the nested partition is applied tends to balance the workload, which in turn reduces makespan.

Table 13 Comparison of the sequence positions for historical data and nested partition (Northbound)

Historical Data

Seq	Position 1	2	3	4	5	6	7	8	9	10	11	12	13
1	DB	C6	DB	C6	DB	C6	T	C8	C6	VC			
2	DB	DB	O	C6	C8	C8	C8	O					
3	DB	VC	DB	DB	C8	VC	VC						
4	C6	O	DB	DB	C6	C8	T						
5	DB	C6	DB	DB	DB	VC	O						
6	T	C8	P6	C6	C6	DB	DB	C6	C8	C6			
7	C8	P6	DB	VC	O	C6	O	VC	C8	C8			
8	C6	DB	DB	DB	DB	DB	C8	C6	VC	C6	VC		
9	T	VC	DB	T	C8	T							
10	T	O	T	C6	O	C6	DB	T	DB	O	T	T	C6
1	C6	T	DB	O	O	C8	VC	T	P6				
2	VC	O	C6	VC	DB	C6	C8	O					
3	P8	T	VC	C6	VC	C8	C8	T	T	T			
4	VC	VC	O	DB	DB	DB	T	C6	C6				
5	C6	C6	O	T	O	C6	O	C6	C8	C6			
6	P8	P6	T	T	DB	VC	T	C6	C8	C8			
7	C8	VC	C6	T	VC	C6	T	C8	C8				
8	VC	T	DB	DB	T	C6	DB	C8	C6	T			
9	C8	VC	O	T	DB	DB	VC	C6	T	C6	C8	O	
10	O	VC	DB	DB	O	C6	T	T	C6	C8	T		

Nested Partition

Seq	Position 1	2	3	4	5	6	7	8	9	10	11	12	13
1	C8	C6	C6	C6	T	C6	DB	DB	DB	VC			
2	C8	C8	C6	O	O	C8	DB	DB					
3	C8	VC	VC	DB	DB	DB	VC						
4	C6	C6	T	O	DB	C8	DB						
5	C6	O	VC	DB	DB	DB	DB						
6	P6	C6	C8	C6	C8	C6	T	C6	DB	DB			
7	P6	C6	C8	C8	C8	O	O	DB	VC	VC			
8	C6	C8	C6	C6	DB	DB	DB	DB	VC	DB	VC		
9	C8	T	T	T	DB	VC							
10	C6	C6	O	C6	O	T	O	T	T	T	DB	O	DB
1	P6	C8	C6	T	O	T	DB	O	VC				
2	C6	C8	O	C6	O	VC	DB	VC					
3	C8	C6	T	T	P8	T	C6	T	VC				
4	C6	C8	C6	O	O	DB	T	DB	DB	VC	VC		
5	C6	C6	C6	C8	T	C6	T	O	O	O			
6	P6	P8	C6	C8	T	C8	C8	T	T	VC			
7	C6	C8	C8	T	C6	T	C8	VC	VC				
8	C6	C8	T	C6	T	T	DB	DB	DB	VC			
9	C6	C8	C8	O	T	C6	T	O	DB	VC	DB	VC	
10	C6	C8	T	C6	T	O	T	O	DB	DB	VC		

Similar phenomena can be observed for southbound schedules as shown in Table 14. The initial position is mostly C8 and the end of the sequence is VC.

Table 14 Comparison of the sequence positions for historical data and nested partition (Southbound)

Historical Data

Seq	Position 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	C6	VC	C6	T	DB	C6	T	DB						
2	DB	C6	DB	DB	DB	DB	DB	C6	C6	T				
3	C6	C8	C6	T	C8	T	VC	VC	C6	DB	VC	T	DB	
4	DB	O	VC	C8	DB	C6	DB	C8						
5	VC	C8	C6	C8	VC	VC	T	T						
6	C6	DB	T	VC	DB	DB	T	C6	DB	T	DB			
7	O	VC	VC	C8	VC	T								
8	VC	C8	T	C8	DB	VC	O	DB	DB	T	T	DB		
9	T	T	T	DB	VC	O	DB	T	O	C6	C8			
10	C8	T	C6	VC	C8	DB	C8	T	VC	O				
1	VC	T	C8	DB	C6	DB	C6	VC						
2	C6	C8	T	C8	C8	C6	VC	DB	DB	DB	C6			
3	VC	C6	C8	DB	VC	VC	DB	DB						
4	VC	T	C8	C6	C8	DB	T	T	DB					
5	VC	T	VC	C8	C8	O	C6	DB	T	O	T	T		
6	C6	C8	O	C8	VC	DB	DB	O	C8					
7	T	C8	C8	C6	C6	DB	T	C6	DB	T	T			
8	C8	C8	DB	DB	C6	DB	DB	DB	DB	O	C6			
9	C6	C6	T	T	C6	DB	T	C6	T	C6				
10	T	C8	C8	C8	C6	VC	T	O	VC	O	T	T	C6	T

Nested Partition

Seq	Position 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	C6	T	T	DB	DB	C6	C6	VC						
2	C8	T	DB	DB	DB	DB	DB	C6	DB	C6				
3	C8	C8	T	DB	T	DB	C6	T	C6	C6	VC	VC	VC	
4	C8	C8	DB	DB	DB	O	C6	VC						
5	C8	C8	T	C6	T	VC	VC	VC						
6	T	DB	DB	T	DB	T	DB	DB	C6	C6	VC			
7	C8	T	O	VC	VC	VC								
8	C8	C8	DB	DB	T	T	T	DB	DB	O	VC	VC		
9	C8	T	T	T	DB	T	DB	O	O	C6	VC			
10	C8	C8	T	C8	T	DB	O	C6	VC	VC				
1	C8	C6	T	DB	DB	VC	C6	VC						
2	T	DB	C8	DB	DB	C8	C6	C6	C6	C8	VC			
3	C8	DB	DB	C6	S	VC	VC	VC						
4	C8	T	DB	T	DB	T	C6	C8	VC					
5	C8	C8	T	T	T	DB	T	O	O	C6	VC	VC		
6	C8	C8	DB	DB	C6	C8	O	O	VC					
7	C8	C8	DB	T	DB	T	T	T	C6	C6	C6			
8	C8	C8	DB	DB	DB	DB	O	DB	O	C6	C6			
9	C6	T	T	DB	T	C6	T	C6	C6	C6				
10	C8	C8	T	T	T	T	T	C6	C8	C6	O	VC	O	VC

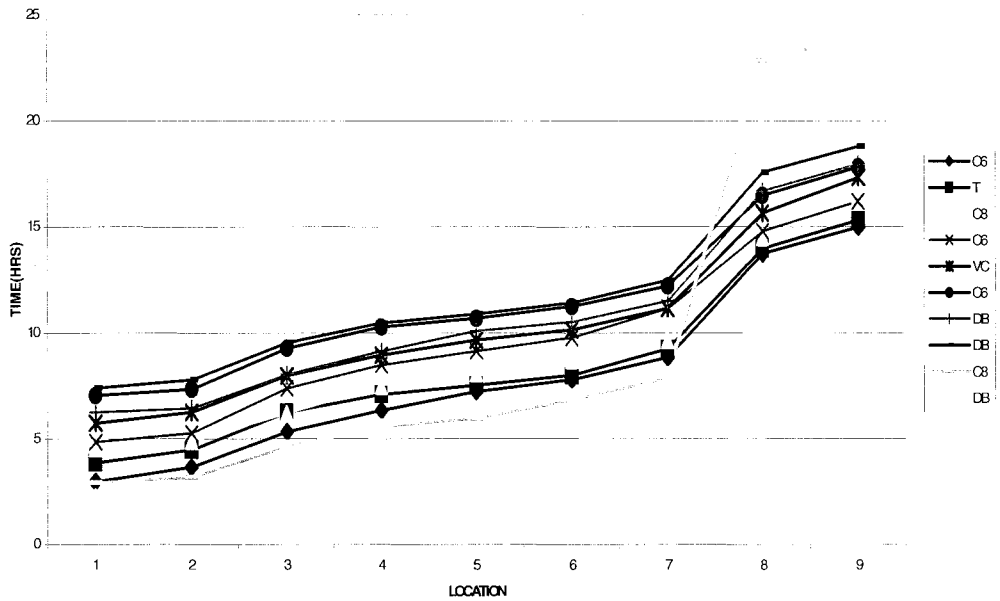


Figure 10 Historical Data Trace. Northbound Sequence 1 sample set1

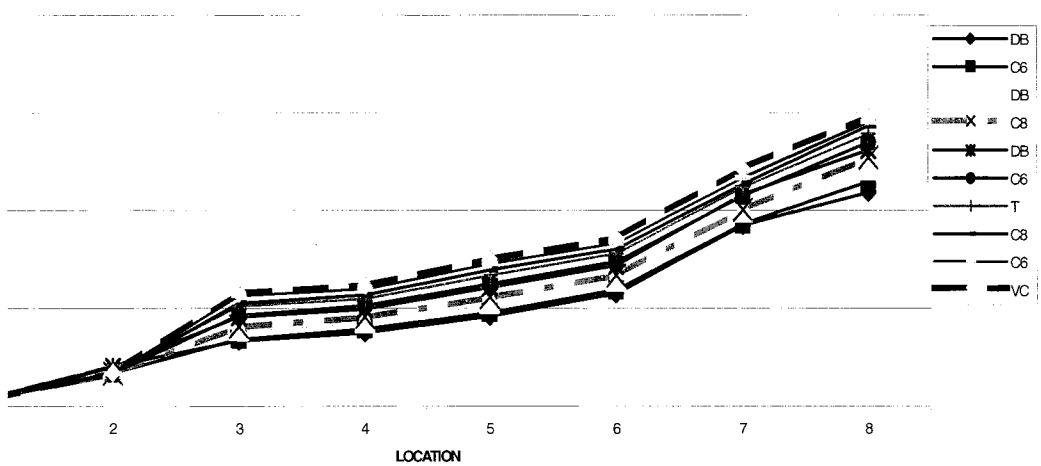


Figure 11 Simulated Data Trace. Northbound Sequence 1 Sample Set 1

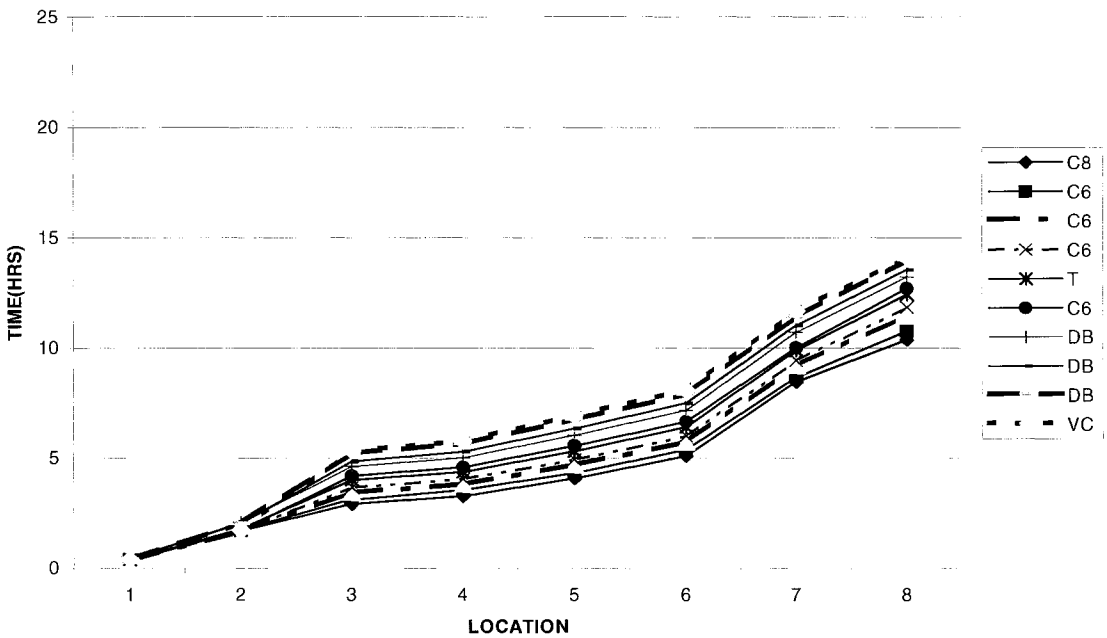


Figure 12 Nested Partition Trace. Northbound Sequence 1 Sample Set 1

To compare the improvement of the Nested Partition schedule to the historical schedule, the throughput (*TP*) was calculated because it normalizes the results based on the number of vessels in the sequence. Tables 15 and 16 present the average percentage improvement in throughput for northbound and southbound schedules. Note that this improvement would increase revenue by $55,000,000 per year. It means an average of 2.43% of improvement for northbound and 3.09% for southbound. The higher throughput of the southbound schedule is due to the omission of the Gatun Locks and Gatun Lake.

The throughput comparison was made with the simulated makespan. The actual makespan is longer than this, so it is expected that the improvement may be higher than 2.43% and that the improvement would be a conservative value.

Table 15 Throughput Comparison- Northbound

Northbound							
Makespan simulation (hr)	**NP (hr)**	**Difference (hr)**	**# of vessels**	**TH NP**	**TH ACTUAL**	**DIFF TH %**	**$ - vessel/hr**
14.017	13.819	0.198	9	0.65	0.64	1.43	1839.95
13.504	13.299	0.205	8	0.60	0.59	1.54	1826.39
14.303	13.823	0.48	10	0.72	0.70	3.47	4855.59
14.931	14.516	0.415	11	0.76	0.74	2.86	4212.45
14.66	14.611	0.049	11	0.75	0.75	0.34	503.27
14.423	14.1	0.323	10	0.71	0.69	2.29	3176.57
13.916	13.713	0.203	9	0.66	0.65	1.48	1914.79
14.689	14.309	0.38	10	0.70	0.68	2.66	3615.86
15.086	14.78	0.306	12	0.81	0.80	2.07	3293.70
14.989	14.648	0.341	11	0.75	0.73	2.33	3416.85
14.811	14.21	0.601	6	0.42	0.41	4.23	3426.71
14.142	13.706	0.436	7	0.51	0.49	3.18	3149.15
13.679	13.156	0.523	8	0.61	0.58	3.98	4649.90
13.432	13.29	0.142	8	0.60	0.60	1.07	1272.75
13.882	13.387	0.495	13	0.97	0.94	3.70	6925.37
14.419	14.172	0.247	7	0.49	0.49	1.74	1692.23
14.351	14.01	0.341	7	0.50	0.49	2.43	2374.45
14.924	14.507	0.417	10	0.69	0.67	2.87	3852.15
13.144	12.853	0.291	10	0.78	0.76	2.26	3445.01
15.638	15.246	0.392	9	0.59	0.58	2.57	2959.52
					AVERAGE	**2.43**	**3120.13**

Table 16 Throughput Comparison- Southbound

Southbound

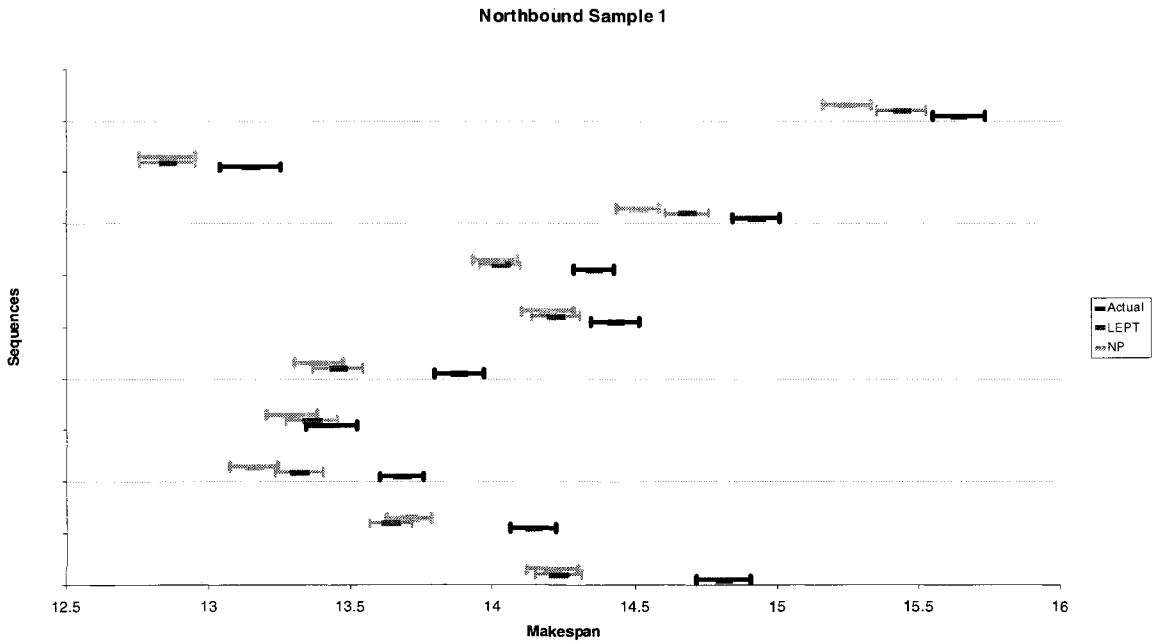
Makespan simulation (hr)	NP (hr)	Difference (hr)	# of vessels	TH NP	TH ACTUAL	DIFF TH %	$-vessel/hr
6.484	6.332	0.103	8	1.26	1.23	2.40	5923.517
7.567	7.374	0.14	10	1.36	1.32	2.62	6917.68
8.162	7.884	0.212	11	1.40	1.35	3.53	9504.39
6.566	6.303	0.186	8	1.27	1.22	4.17	10167.81
6.364	6.132	0.213	13	2.12	2.04	3.78	15457.14
7.886	7.600	0.276	10	1.32	1.27	3.76	9543.895
5.688	5.374	0.294	5	0.93	0.88	5.84	10272.41
8.035	7.804	0.14	8	1.03	1.00	2.96	5894.254
7.695	7.455	0.205	12	1.61	1.56	3.22	10040.75
7.220	6.928	0.233	11	1.59	1.52	4.21	12842.82
6.297	6.211	0.086	8	1.29	1.27	1.38	3518.222
7.512	7.364	0.148	11	1.49	1.46	2.01	5885.929
6.382	6.173	0.209	8	1.30	1.25	3.39	8488.153
6.933	6.823	0.11	9	1.32	1.30	1.61	4185.705
7.916	7.645	0.271	12	1.57	1.52	3.54	10747.25
6.771	6.567	0.204	9	1.37	1.33	3.11	8258.151
7.862	7.583	0.279	11	1.45	1.40	3.68	10295.63
7.672	7.618	0.054	11	1.44	1.43	0.71	2032.67
7.175	7.139	0.036	10	1.40	1.39	0.50	1405.637
8.716	8.278	0.438	14	1.69	1.61	5.29	16997.67
					AVERAGE	**3.09**	**8418.98**

The improvements with the rules and the differences with the Nested Partition method are similar (as shown in Table 17), indicating that the rules appear to be working correctly.

Table 17 Makespan Improvements

	Northbound		Southbound	
	Difference	Difference	Difference	Difference
Sequences	SEPT %	NP%	LEPT%	NP%
1	0.41	0.94	0.21	1.37
2	0.89	1.52	1.09	1.12
3	0.56	3.36	2.37	3.27
4	2.41	2.78	0.92	1.59
5	0.31	0.33	2.68	3.42
6	1.53	2.24	1.86	2.38
7	0.94	1.46	2.73	3.55
8	1.90	2.59	-0.38	0.38
9	1.04	1.43	0.08	0.50
10	2.22	2.28	3.85	5.03
11	3.92	4.06	1.59	2.34
12	3.54	3.08	1.85	2.55
13	2.65	3.82	2.60	3.41
14	0.52	1.06	2.83	4.01
15	3.08	3.57	3.35	3.65
16	1.39	1.71	3.50	3.63
17	2.25	2.38	5.17	5.52
18	1.64	2.79	1.74	2.87
19	2.21	2.21	2.66	3.12
20	1.28	2.51	3.23	4.04

Figures 13 and 14 show the performance comparison of the schedules for northbound and southbound vessel sets. The confidence intervals were calculated for each one and compared. It appears that the Nested Partition method in most cases produces statistically significant improvements in the makespan over historical data. From the twenty sequences for northbound dataset, two were equivalent. The order of these sequences is quite similar with the historical data. Similar results were obtained for the southbound dataset.



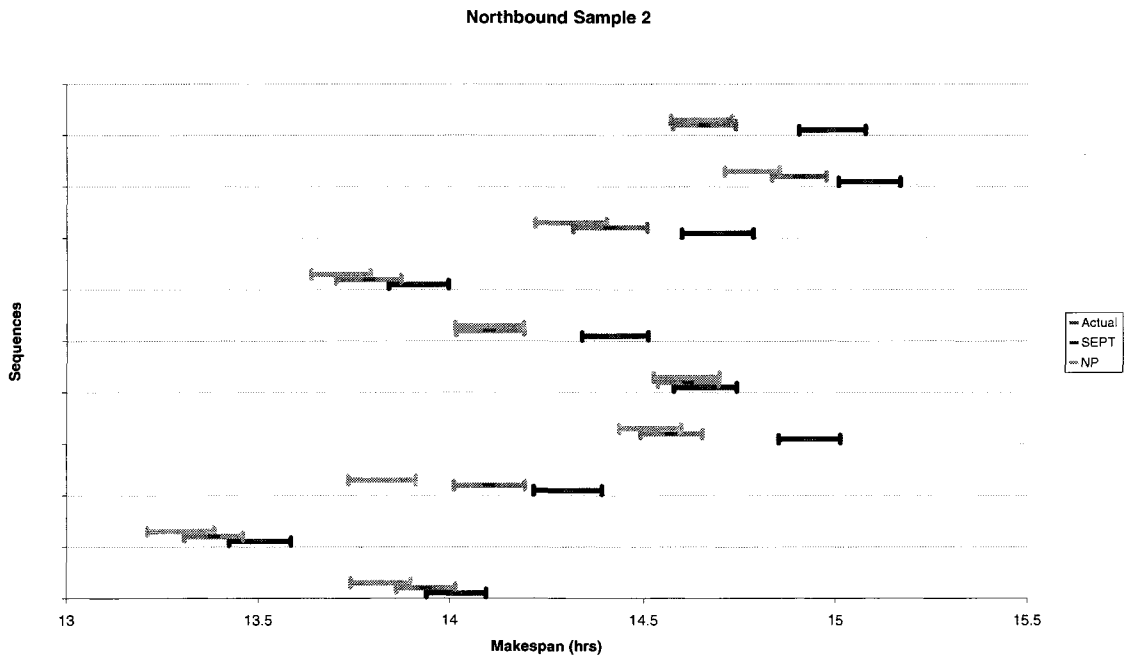
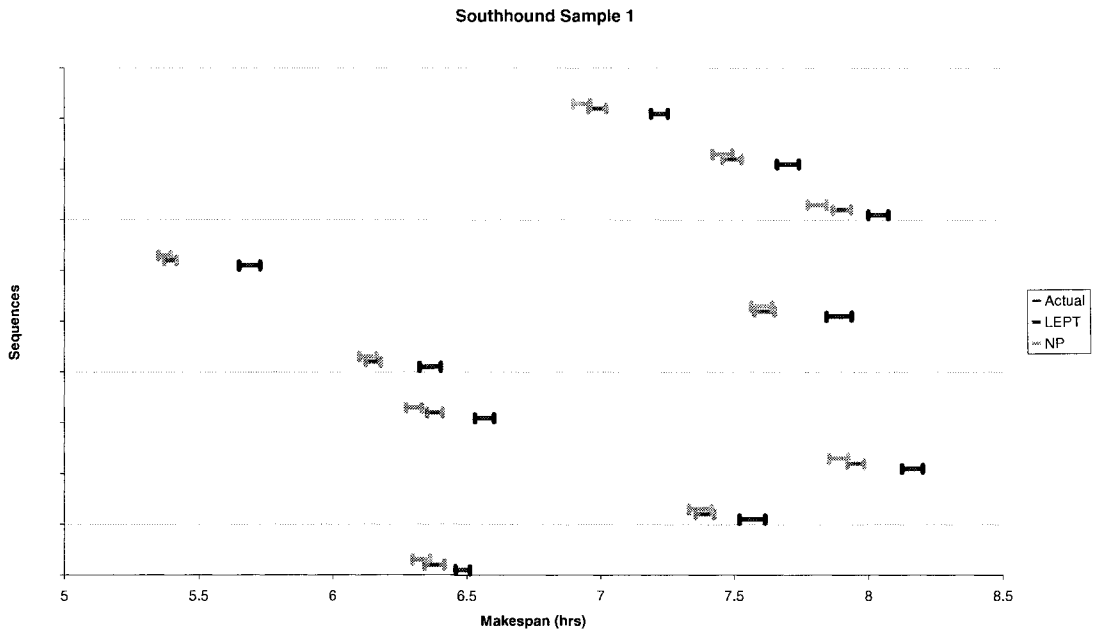


Figure 13 Confidence Intervals Comparison for Northbound



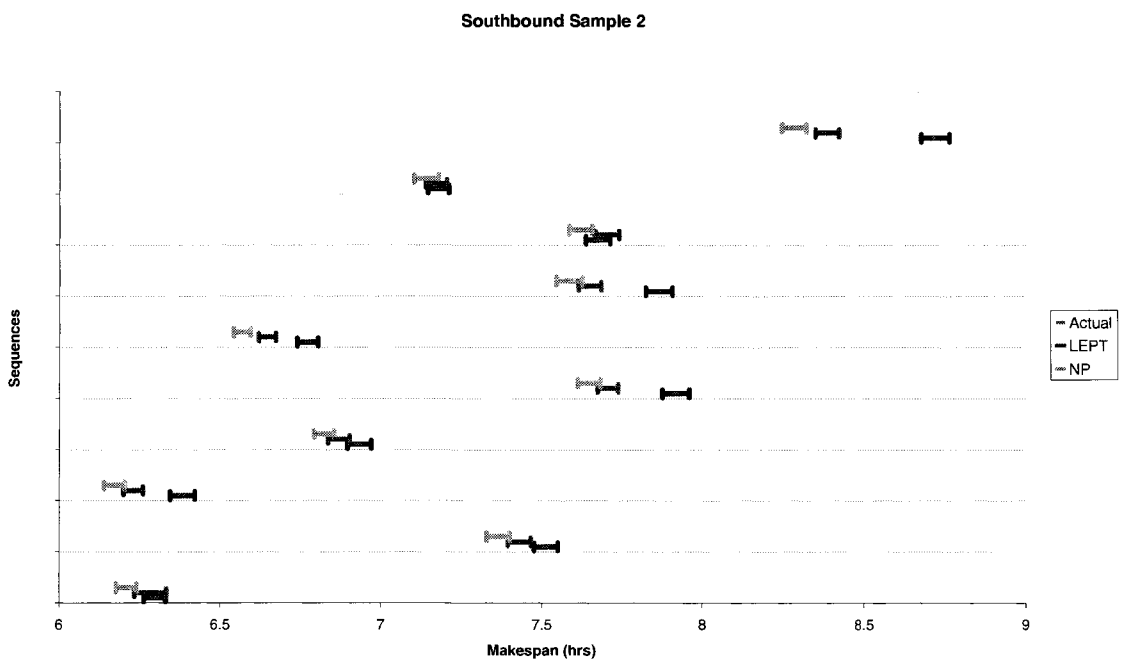


Figure 14 Confidence Intervals Comparison for Southbound

To examine the similarities between multiple good schedule solutions, a set of 4 of the 40 samples was randomly selected and run for minimum sample size of 5, 10 and 20. The schedules are shown in Figures 15, 16, 17 and 18. The results show different schedules with equivalent performance in terms of makespan. Each row is a separate run of the Nested Partition method for the same vessel sequence. The columns from left to right are the sequence of vessels in the schedule. The numbers at the bottom are the fraction of times (i.e., frequency) that the vessel type appears in that position of the sequence. A value of 1 indicates that it is always in that position. If there is no value, the vessel type never appears in that position.

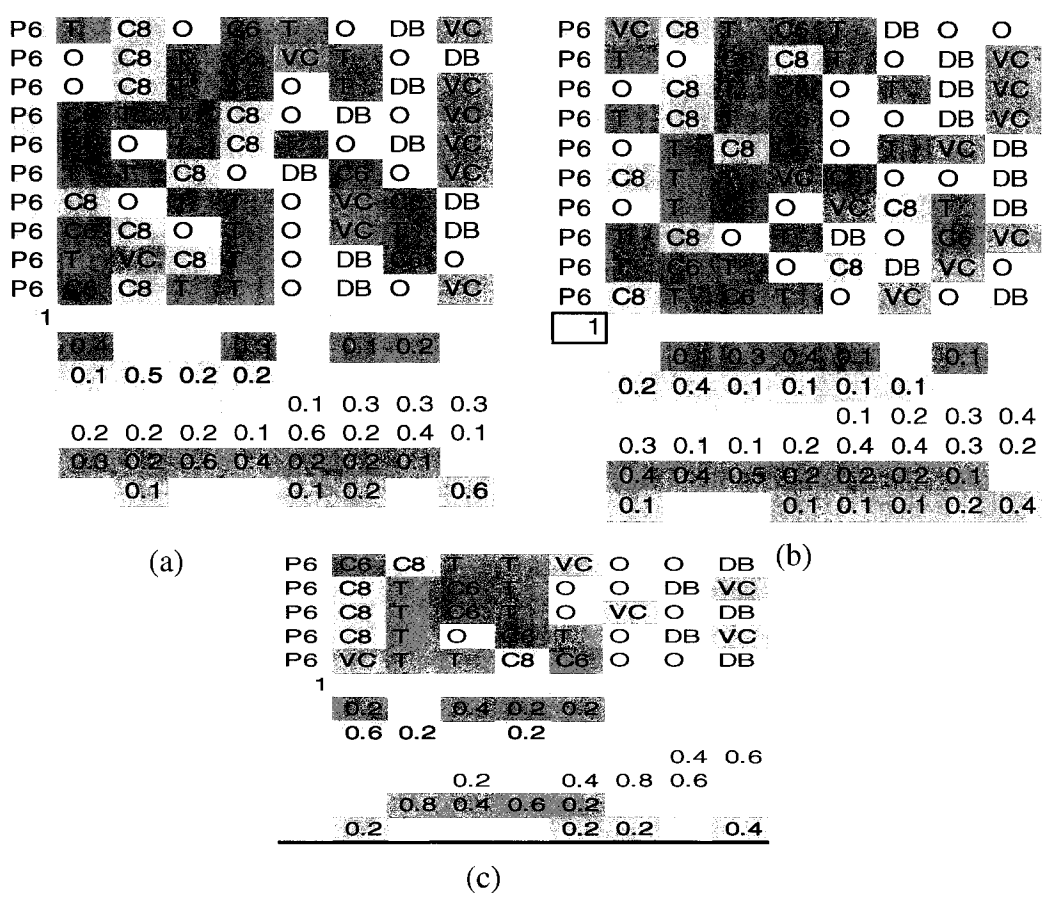


Figure 15 Set 1 of Northbound sequences with different minimum sample size
(a) Minimum sample size = 5 (b) Minimum sample size =10 (c) Minimum sample size = 20

It seems that the critical positions in the sequences are at the beginning and the end. There appears to be a pattern having certain vessels types in these positions. For the northbound schedule, the first position is for Passenger 6 in the first set and in the second set Container 6 or Container 8. Vehicle Carrier or Dry Bulk vessels appear at the end of the sequences and the center positions are usually Tankers and Others, in that order.

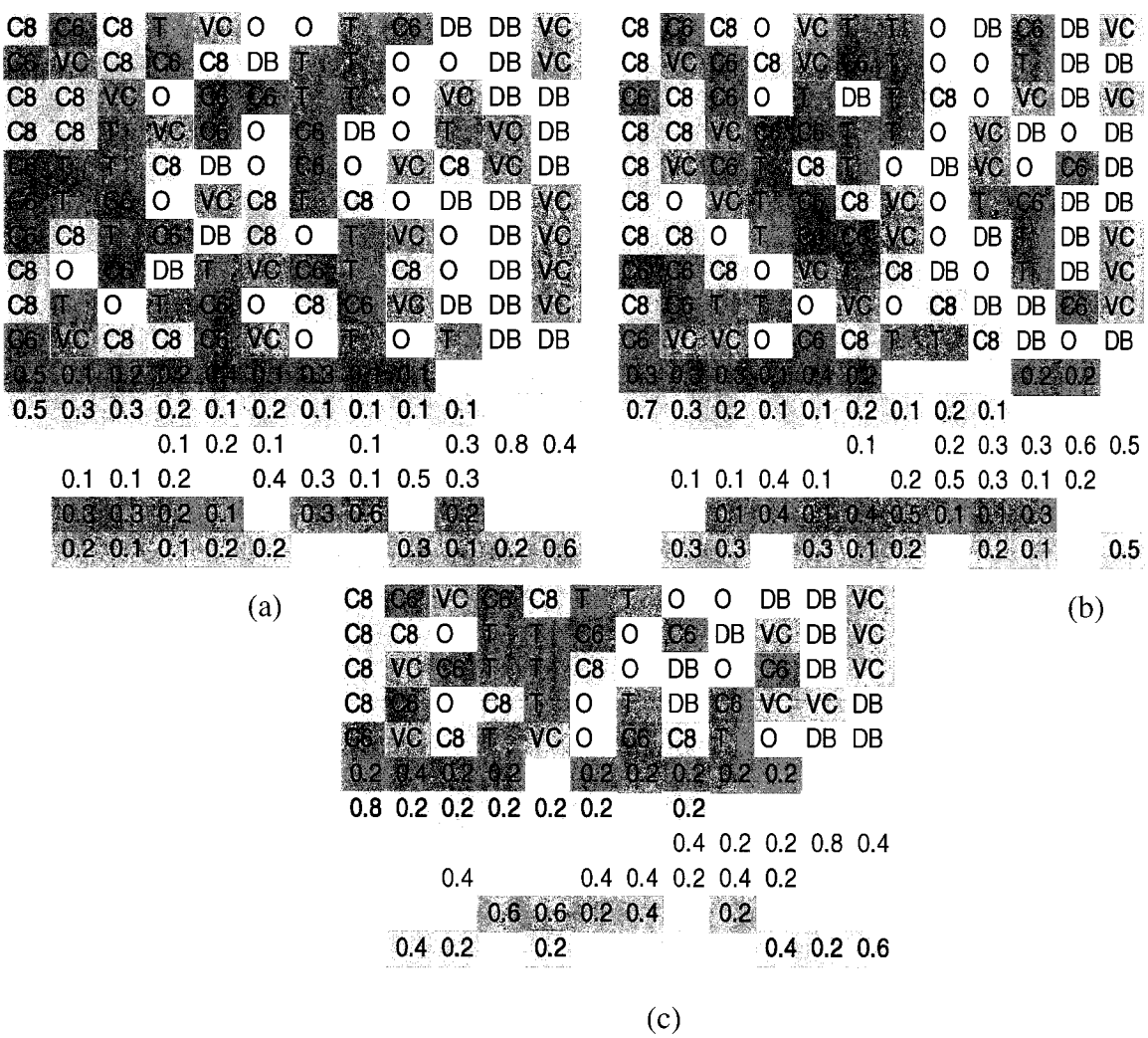


Figure 16 Set 2 of Northbound sequences with different minimum sample size
(a) Minimum sample size = 5 (b) Minimum sample size = 10 (c) Minimum sample size = 20

For southbound schedules, the first position appears to be Container 8 for both sets, followed by Tanker and Dry Bulk vessels. Container 6, Others, and Vehicle Carrier usually appear at the end. Vehicle Carrier vessels are consistently appearing at the end.

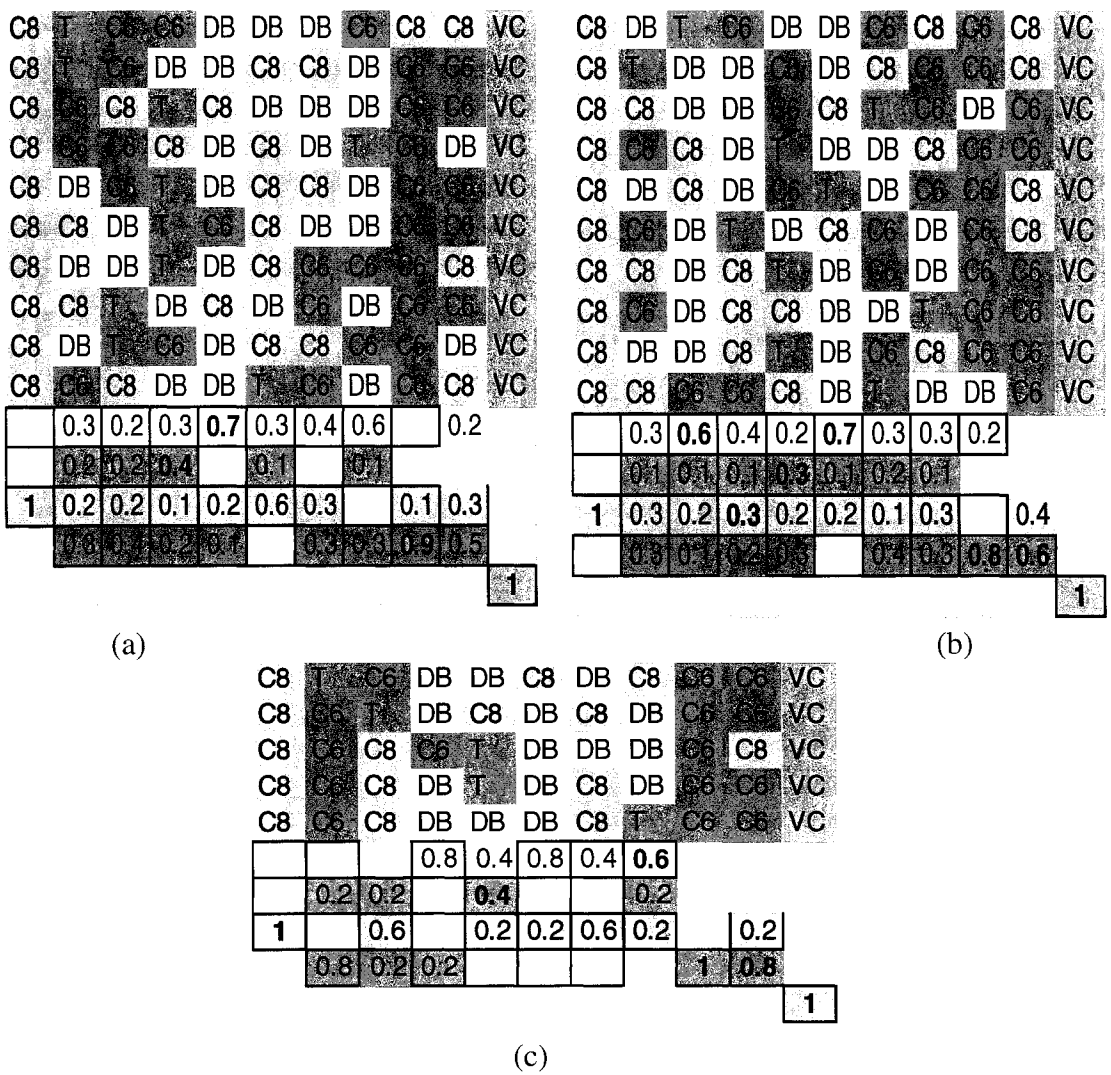


Figure 17 Set 1 of Southbound sequences with different minimum Sample Size
(a) Minimum sample size = 5 (b) Minimum sample size = 10 (c) Minimum sample size = 20

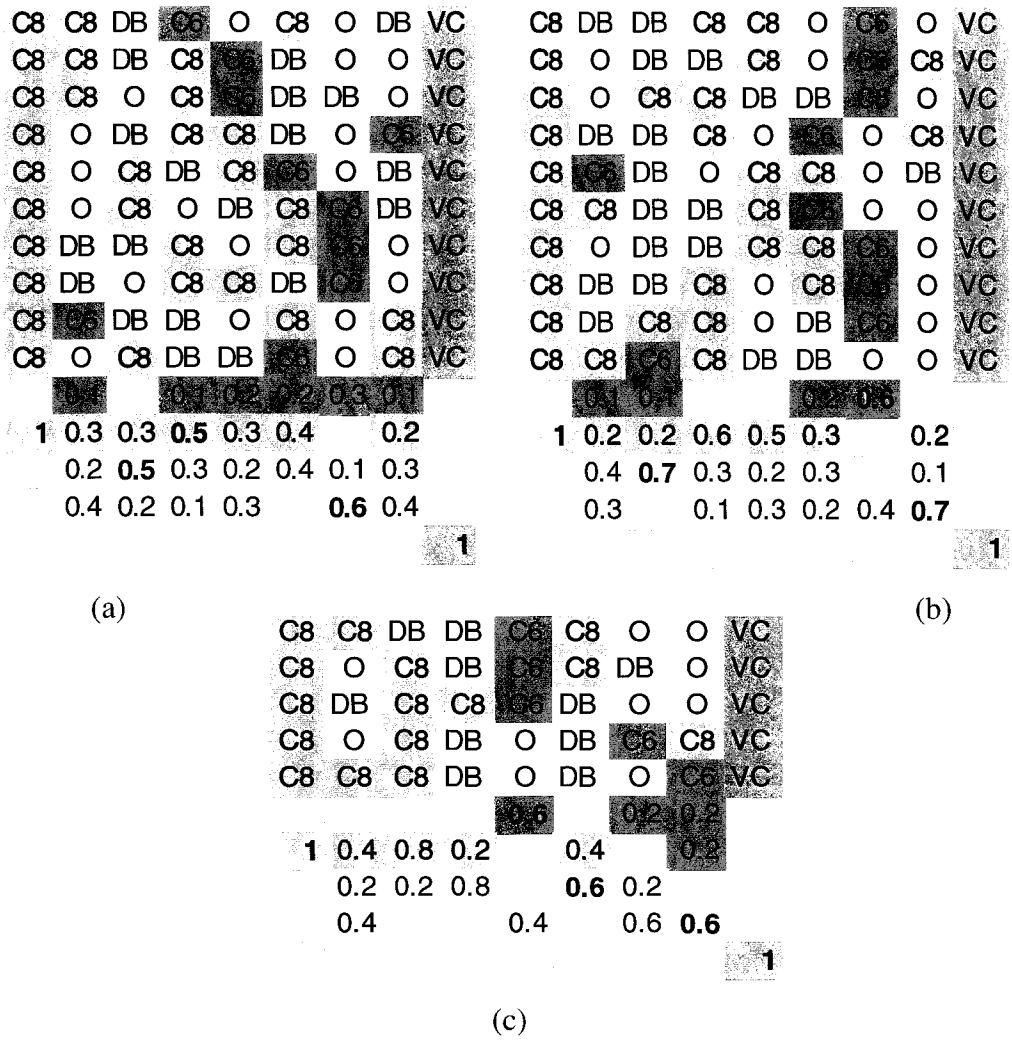


Figure 18 Set 2 of Southbound sequences with different minimum Sample Size
(a) Minimum sample size = 5 (b) Minimum sample size = 10 (c) Minimum sample size = 20

6 CONCLUSIONS AND FUTURE WORK

This research has addressed a real world scheduling system problem. The main characteristics are: stochastic processing times, flow shop machine environment, four stages with parallel and single machines, and two-way flow. The objective function was to minimize the time required to complete the transit of the vessels in Panama Canal or the maximum completion time called makespan (C_{max}). The major conclusions of this research are as follows.

Panama Canal can be modeled as a Flexible Flow Shop with four stages, three of them as parallel machines and one as single machine. The probability distributions for processing times indicate significant differences between vessel types at different stages. Analysis of historical data indicated that processing times had either a beta, normal, or uniform time distribution depending on the type of vehicle. Differences between vessel types were observed for the mean and standard deviation.

The Nested Partition method, a metaheuristic technique, was used to find schedules that reduce the makespan. The use of this technique produced multiple good schedules. The method backtracked on average one to two times and switched two to four times. The partition process with random sampling obtained a solution in a relatively short period of time (< 0.5 hour) and therefore, it is well suited for real time applications. Evaluation of the results of the simulation model using real data from the Panama Canal indicated that the model behavior is similar to the actual system. The results show that the proposed scheduling approach performs significantly better than simple heuristics used by schedulers at the

Panama Canal, providing evidence to support the hypothesis of this study. The improvement represents an increase of $55,000,000 for the PCA on an annual basis. This is considered to be a conservative estimate.

Choosing the rule for the initial partition is a very important step in the application of the Nested Partition Method because the search concentrates on the most promising region where the best solutions should be located. Initial rules based on longest expected processing time had to be modified based on the performance of the Nested Partition method. Unsatisfactory rules result in backtracking to the first level (P_0), indicating that the best solutions are not in the most promising region. A good rule eliminates backtracking to P_0 and significantly reduces the set of feasible solutions.

The SEPT rule for the northbound direction and the modified LEPT rule for the southbound direction appear to consistently identify the most promising region for the Nested Partition method, producing schedules that perform well in terms of makespan. In a number of cases, the schedules based on the rules performed as well as those from the Nested Partition method. Schedule improvements can be made by applying these simple rules and then use a local search technique at each stage to improve upon the initial solution.

Analysis of the patterns for good schedules (obtained with the Nested Partition method for four sets of sequences) showed that northbound and southbound schedules that perform well have distinct patterns based on vessel type. The beginning and end of a sequence appears to be critical positions when assigning vessels to the schedule. The first position in the sequence for northbound appear to be passenger 6(P6), when P6 is not in the

set of vessels to schedule then container 6 (C6) or container 8 (C8) should be in the first position. At the last position vehicle carrier (VC) or dry bulk should be scheduled. For southbound, the first position in the sequence appear to be for C8 and the last position for VC.

Based on the results of this study, the following recommendations can be made for scheduling large vessels in the Panama Canal.

1. Given that some data values in the historical record are missing and processing times in each chamber in the locks are not available, more accurate and detailed data should be collected.

2. Use the SEPT rule for northbound schedules according to the Gatun Lake order of the vessels and LEPT for southbound using the PM Locks order of vessels in combination with the Nested Partition method in order to find a good schedule.

3. If the rules are used without the Nested Partition method, use the patterns obtained for the best sequences. Schedule P6 in the first position of the sequence for northbound schedules. If P6 is not in the vessel set, then C6 or C8 should be in the first position and VC or DB at the end. For southbound schedules, C8 should be scheduled in the first position of the sequence. When C8 is not in the set of vessels, then C6 should be in the first position and VC at the end.

6.1 Future Work

The order of vessels was the same fixed sequence at each of the four stages. Further investigations are warranted to determine the effects of relaxing this constraint and allowing different sequences at different stages. Changes in the sequence will be somewhat limited between the Gaillard Cut and the MF Locks due to the limited space, which would prevent major changes in sequences. The large buffer capacity of Gatun Lake provides an opportunity to make major changes in sequences. Therefore, for two separate sequences could be considered, namely, one for Gatun Locks and one for the other stages.

In this model the effect of bidirectional flow was seen in the entrance to the Gaillard Cut. In the night and sometimes in Gatun Lock, vessels (typically small sizes) from northbound and southbound can pass each other. A major extension to this model would be the inclusion of smaller vessels and the bidirectional flow.

The resource allocation problem at each of the locks was not considered in this model. Additional work is needed to determine the impact of resource allocation decisions on schedule performance. By including the limited capacity resources (e.g., locomotives, linehandlers, and tugboats) in the model, additional insights can be obtained into resource utilization and associated costs.

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APPENDIX A

The data for this study was collected in spreadsheets by the Panama Canal Authority. This data has all the information about the operations in the Panama Canal. The data covers vessel transit from arrival to departure. The dataset includes years 2003-2004 in which 24,798 vessels transited the canal. Of these vessels, 12,321 were vessels greater than 91 feet of beam. The number of large vessels in the northbound direction was 5,517 and in the southbound direction, 6,804. The dataset includes: the dates of transit, identification number, draft, beam, length, type, direction, destination and origin, market segment, number of resources used, lane used in the locks, and all the times from the enter to the end of the canal. The Panama Canal Authority also provided data about the fog time, operations, scheduling procedures, and resources needed for transits.

A subset of the dataset was created for the 12, 321 vessels, which are greater than 91 feet of beam. This subset was then analyzed, classified according to the segment market and probability distributions were fitted using the JMP software. The vessel data was divided in Northbound and Southbound to facilitate the study.

Table A.1 Processing Time Distributions for Northbound Vessels

Vessel Type		Underway Time	Buoy1-MF	MF Locks	MF-PM	PM Locks	PM-Gamboa	Gamboa-GT	GT Locks	GT-Buoy1a
	Distribution	Normal	Beta	Normal	Normal	Normal	Normal	Beta	Normal	Normal
Container 6	Mean	0.38	1.313	0.49	0.347	0.57	0.52	3.38	0.505	0.6192
	S.D.	0.13	0.25	0.07	0.069	0.07	0.0325	0.025576	0.05	0.079
	α (Alpha)		2.85					2.03		
	β (Beta)		3.52					5		
	θ (Theta)		0.72					1.97		
	σ (Sigma)		1.346					4.91		
	Distribution	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Container 8	Mean	0.43	1.26	0.52	0.347	0.64	0.52	3.4	0.57	0.6192
	S.D.	0.14	1.18	0.03	0.069	0.08	0.0325	0.71	0.0575	0.079
	Distribution	Normal	Normal	Beta	Normal	Normal	Normal	Beta	Beta	Normal
Tankers	Mean	0.41	1.36	0.49	0.35	0.6	0.52	3.44	0.52	0.6192
	S.D.	0.14	0.26	0.1	0.07	0.18	0.0325	0.86	0.02	0.079
	α (Alpha)			4.53				2.48	1.53	
	β (Beta)			16.7				7.09	11.938	
	θ (Theta)			0.27				1.76	0.422	
	σ (Sigma)			1.075				6.45	0.942	
	Distribution	Normal	Normal	Beta	Beta	Beta	Normal	Normal	Beta	Normal
Dry Bulk	Mean	0.45	1.58	0.545	0.388	0.58	0.56	3.55	0.51	0.6585
	S.D.	0.14	0.29	0.055	0.072	0.11	0.07	0.78	0.08	0.08
	α (Alpha)			2.11	2.736	4.14			1.71	
	β (Beta)			5.6	11.96	10.4			4.15	
	θ (Theta)			0.34	0.23	0.33			0.37	
	σ (Sigma)			0.77	0.85	1.27			0.47	
	Distribution	Normal	Normal	Normal	Normal	Normal	Normal	Beta	Beta	Normal
Vehicle Carrier	Mean	0.385	1.325	0.465	0.33	0.53	0.52	3.57	0.51	0.58
	S.D.	0.123	0.2416	0.0375	0.07	0.06	0.0325	0.73	0.02	0.07
	α (Alpha)							2.08	2.027	
	β (Beta)							1.79	11.91	
	θ (Theta)							1.8	0.35	
	σ (Sigma)							3.29	0.53	
	Distribution	Normal	Normal	Beta	Normal	Normal	Normal	Beta	Beta	Normal
Others	Mean	0.412	1.325	0.52	0.37	0.61	0.54	3.48	0.503	0.6192
	S.D.	0.14	0.2416	0.0425	0.07	0.12	0.07	0.72	0.017	0.079
	α (Alpha)			1.52				1.54	1.05	
	β (Beta)			3.05				2.3	5.31	
	θ (Theta)			0.374				2.07	0.43	
	σ (Sigma)			0.429				3.63	0.45	
	Distribution	Normal	Uniform	Beta	Normal	Beta	Normal	Beta	Normal	Normal
Passengers 6	Mean	0.29	1.3	0.52	0.37	0.343324	0.5	3.31	0.46	0.59
	S.D.	0.11	0.23094	0.0092	0.09	0.014378	0.06	0.020472	0.06	0.06
	α (Alpha)	a	0.9	5.05		5.04		1.4		

	β (Beta)		b 1.7	14.67		9.64		5.5		
	θ (Theta)			0.33		0.34		2.35		
	σ (Sigma)			0.74		0.71		4.73		
	Distribution	Normal	Uniform	Uniform	Uniform	Normal	Uniform	Uniform	Uniform	Uniform
Passengers	Mean	0.33	1.3	0.5	0.35	0.56	0.49	3.425	0.55	0.625
8	S.D.	0.16	0.23094	0.0577	0.0433	0.07	0.063509	0.460208	0.028868	0.043301
	a		0.9	0.4	0.275		0.38	2.25	0.5	0.55
	b		1.7	0.6	0.425		0.6	4.6	0.6	0.7

Table A.2 Processing Time Distributions for Southbound Vessels

Vessel Type		Underway	Buoy1a-GT	GT Locks	GT-Gamboa	Gamboa-PM	PM Locks	PM-MF	MF Locks	MF-Buoy1
	Distribution	Normal	Normal	Normal	Beta	Beta	Normal	Normal	Normal	Normal
Container 6	Mean	0.28	1.07	0.47	3.02	0.615	0.61	0.42	0.46	0.88
	S.D.	0.16	0.21	0.02	0.7	0.03	0.08	0.13	0.06	0.09
	α (Alpha)				1.24	2.78				
	β (Beta)				2.02	3.6				
	θ (Theta)				1.9	0.41				
	σ (Sigma)				2.94	0.53				
	Distribution	Normal	Normal	Beta	Beta	Beta	Normal	Normal	Normal	Beta
Container 8	Mean	0.28	1.11	0.51	3	0.5	0.71	0.42	0.49	0.86
	S.D.	0.16	0.23	0.03	0.7	0.02	0.13	0.13	0.05	0.07
	α (Alpha)			17.65	1.44	2.66				9.51
	β (Beta)			20.25	4.15	5				3.5
	θ (Theta)			0.16	1.96	0.434				0.43
	σ (Sigma)			0.87	3.89	0.57				0.58
	Distribution	Normal	Beta	Beta	Beta	Beta	Normal	Beta	Beta	Normal
Tankers	Mean	0.28	1.086	0.53	3.05	0.51	0.75	0.46	0.5	0.94
	S.D.	0.16	0.2	0.05	0.77	0.05	0.17	0.14	0.04	0.11
	α (Alpha)		2.16	2.147	1.29	2.6		3.8	6.4	
	β (Beta)		7.83	3.16	3.71	3.55		11.54	19.23	
	θ (Theta)		0.736	0.38	1.98	0.44		0.17	0.3	
	σ (Sigma)		1.76	0.4	4.2	0.54		1.19	0.925	
	Distribution	Normal	Beta	Normal	Beta	Normal	Normal	Normal	Normal	Normal
Dry Bulk	Mean	0.29	1.11	0.587	3.2	0.69	0.764	0.495	0.48	0.99
	S.D.	0.17	0.2	0.098	0.73	0.055	0.14	0.17	0.04	0.09
	α (Alpha)		1.84		1.13					
	β (Beta)		2.55		2.97					
	θ (Theta)		0.72		2.28					
	σ (Sigma)		0.92		3.45					
	Distribution	Normal	Normal	Normal	Beta	Beta	Beta	Beta	Normal	Normal
Vehicle Carrier	Mean	0.28	1.07	0.473	3.3	0.6	0.54	0.4	0.41	0.88
	S.D.	0.16	0.21	0.02	0.86	0.05	0.07	0.09	0.02	0.08
	α (Alpha)				1.51	6.86	2.85	4.89		
	β (Beta)				3.99	15.43	7.67	14.98		
	θ (Theta)				1.78	0.29	0.39	0.18		
	σ (Sigma)				4.62	1.05	0.56	0.88		
	Distribution	Normal	Beta	Beta	Beta	Beta	Beta	Beta	Normal	Normal
Others	Mean	0.28	1.05	0.48	3.35	0.64	0.65	0.38	0.48	0.94
	S.D.	0.16	0.17	0.05	0.63	0.04	0.11	0.07	0.04	0.11
	α (Alpha)		1.53	6.92	1.305	9.17	2.75	1.71		
	β (Beta)		1.38	23.9	2.423	19.04	6.69	1.94		
	θ (Theta)		0.69	0.3	2.35	0.3	0.42	0.248		
	σ (Sigma)		0.67	0.9	2.84	1	0.76	0.29		

	Distribution	Normal	Normal	Normal	Uniform	Uniform	Beta	Beta	Normal	Uniform
Passengers 6	Mean	0.26	1.07	0.47	3.005	0.625	0.68	0.38	0.48	0.9
	S.D.	0.11	0.16	0.02	0.805	0.101	0.18	0.0126	0.04	0.087
	α (Alpha)			a	1.61	0.45	2.56	3.02	a	0.75
	β (Beta)			b	4.4	0.8	54.6	10.06	b	1.05
	θ (Theta)						0.49	0.16		
	σ (Sigma)						3.96	0.98		
	Distribution	Normal	Beta	Normal	Uniform	Uniform	Uniform	Uniform	Beta	Uniform
Passengers 8	Mean	0.26	1.18	0.515	3.165	0.65	0.7	0.425	0.52	0.95
	S.D.	0.11	0.29	0.06	0.857	0.144	0.612	0.072	0.02	0.115
	α (Alpha)		2.77	a	1.68	0.4	0.65	0.3	7.89	0.75
	β (Beta)		3.74	b	4.65	0.9	0.75	0.55	30.53	1.15
	θ (Theta)		0.65						0.35	
	σ (Sigma)		1.13						0.86	

APPENDIX B

Performance Comparison for Nested Partition Method with different Minimum Sample Size

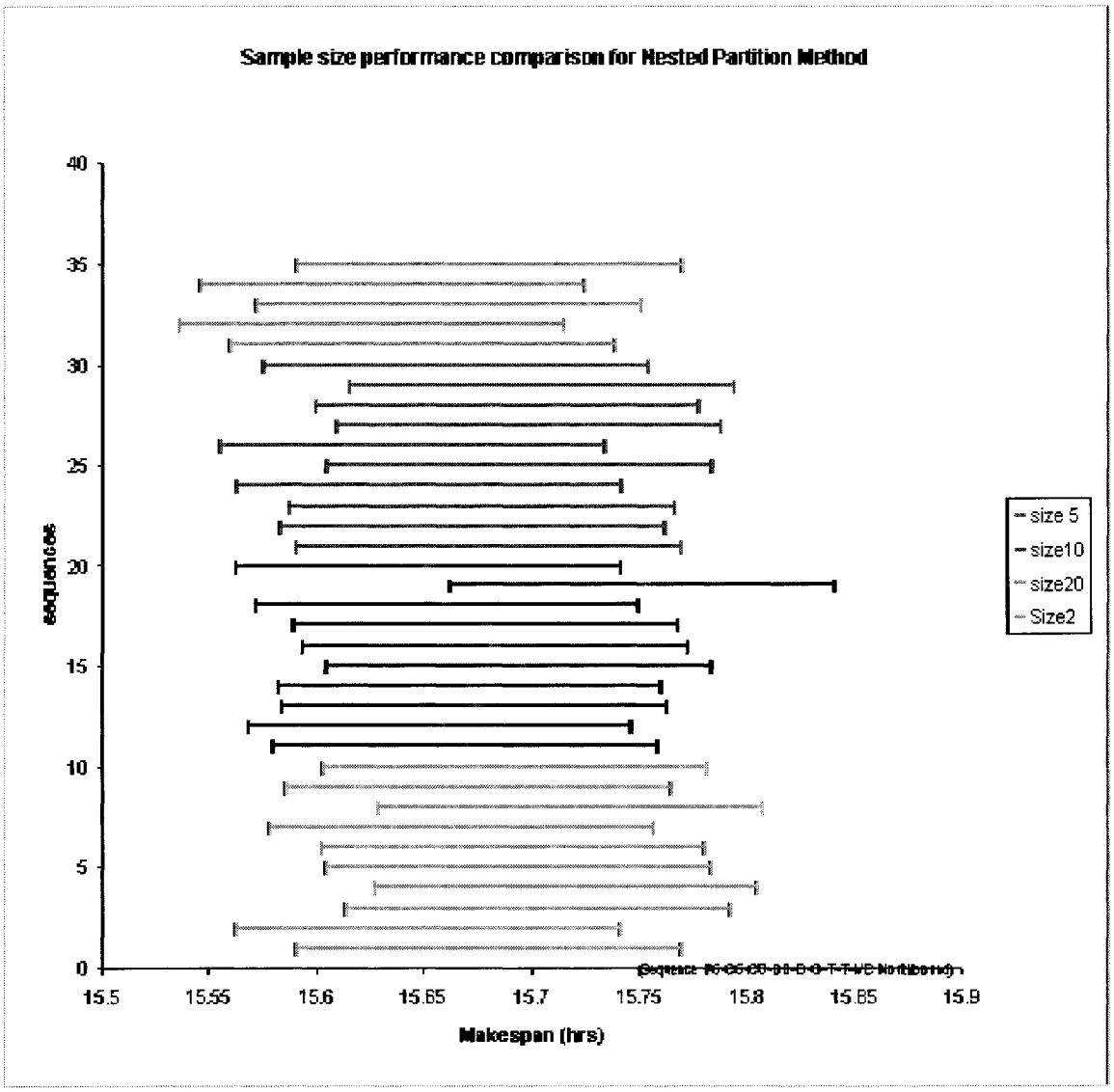

Figure B1 Performance Comparison for Northbound –Sequence 1 of Sample Set 2

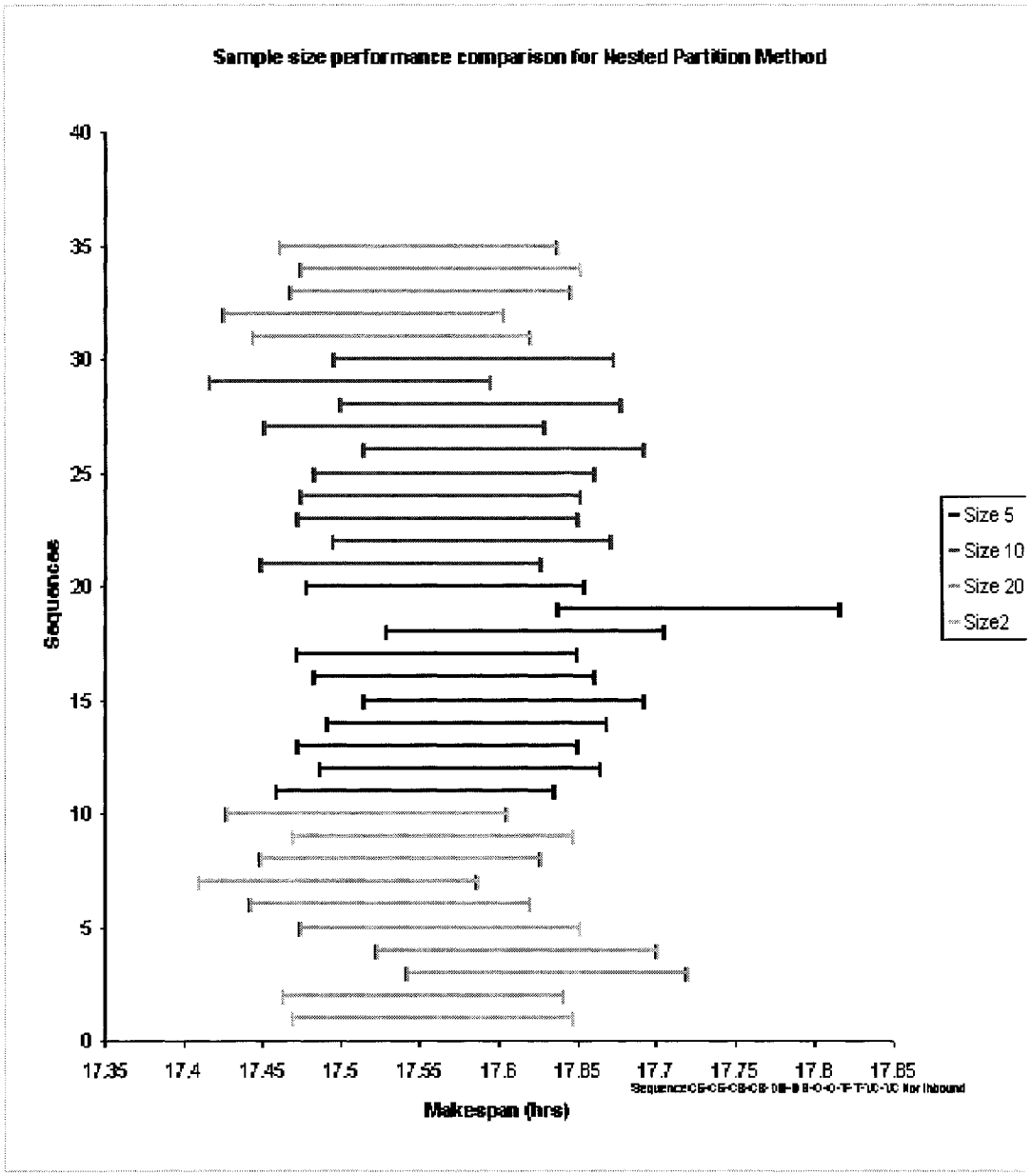

Figure B2 Performance Comparison for Northbound –Sequence 9 of Sample Set 2

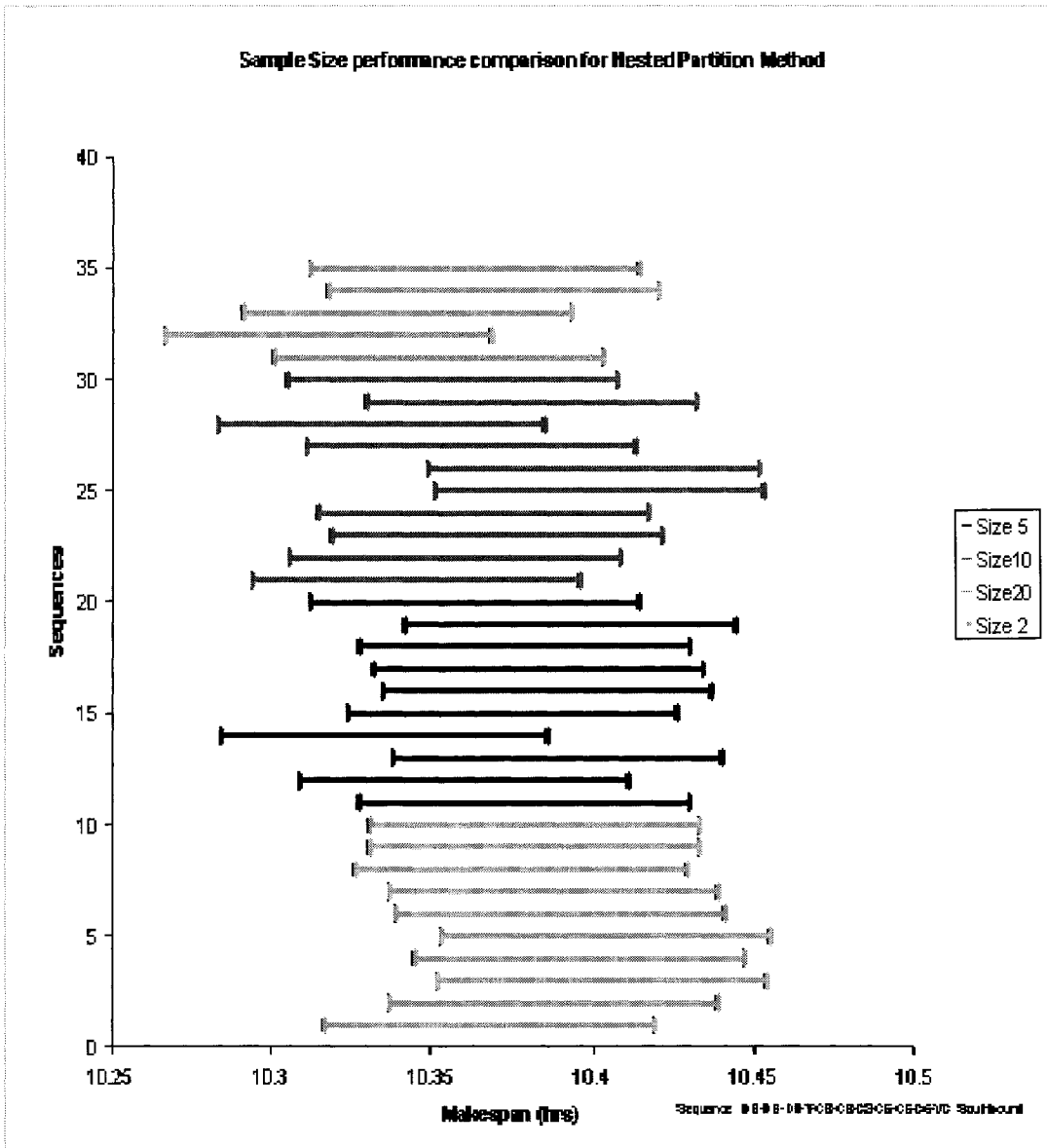

Figure B3 Performance Comparison for Souhbound –Sequence 2 of Sample Set 2

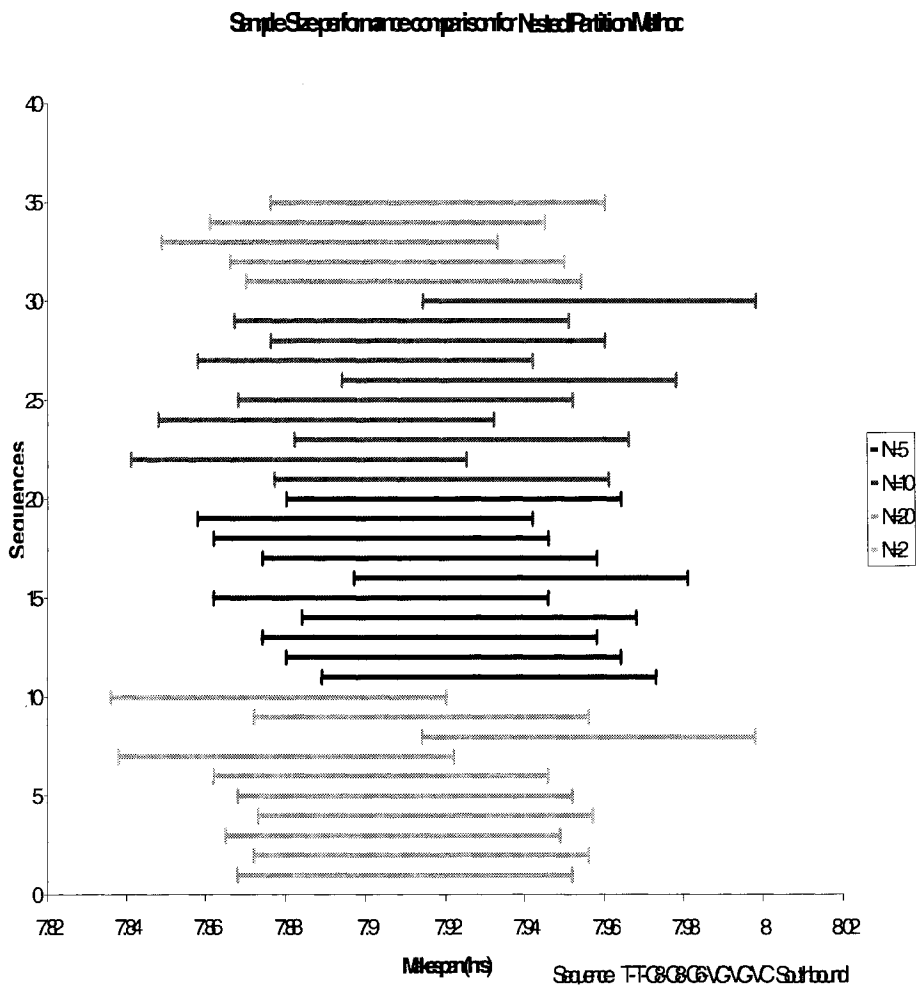

Figure B4 Performance Comparison for Southbound –Sequence 5 of Sample Set 1

APPENDIX C

Confidence Intervals for Nested Partition and Actual and Rules. Northbound and Southbound. Sample Set 1 and 2

Table C1 Confidence Intervals for Northbound Sample set 1

Sample #1				Confidence Interval				Confidence Interval			Confidence Interval		
Seq #	Transit Date	Data Seq	C_{max} Sim	L	U	LEPT Seq	C_{max} LEPT	L	U	NP Seq	C_{max} NP	L	U
1	29-Nov-02	Dry Bulk	14.81	14.72	14.91	Container6	14.23	14.15	14.31	C8	14.21	14.12	14.3
	29-Nov-02	Container				Container6				C6			
	29-Nov-02	Dry Bulk				Container6				C6			
	29-Nov-02	Container				Container6				C6			
	29-Nov-02	Dry Bulk				Container				T			
	29-Nov-02	Container				Tankers				C6			
	29-Nov-02	Tankers				Dry Bulk				DB			
	29-Nov-02	Container				Dry Bulk				DB			
	29-Nov-02	Container				Dry Bulk				DB			
	29-Nov-02	VC				VC							
2	19-Jan-03	Dry Bulk	14.14	14.06	14.22	Container6	13.64	13.57	13.72	C8	13.71	13.63	13.78
	19-Jan-03	Dry Bulk				Container				C8			
	19-Jan-03	Others				Container				C6			
	19-Jan-03	Container				Container				O			
	19-Jan-03	Container				Others				O			
	19-Jan-03	Container				Others				C8			
	19-Jan-03	Container				Dry Bulk				DB			
	19-Jan-03	Others				Dry Bulk				DB			
3	23-Feb-03	Dry Bulk	13.68	13.6	13.76	Container	13.32	13.23	13.4	C8	13.16	13.07	13.24
	23-Feb-03	VC				Dry Bulk				VC			
	23-Feb-03	Dry Bulk				Dry Bulk				VC			
	23-Feb-03	Dry Bulk				Dry Bulk				DB			
	23-Feb-03	Container				VC				DB			
	23-Feb-03	VC				VC				DB			
	23-Feb-03	VC				VC				VC			
4	29-Mar-03	Container	13.43	13.34	13.52	Container6	13.36	13.27	13.45	C6	13.29	13.2	13.38
	29-Mar-03	Others				Container6				C6			
	29-Mar-03	Dry Bulk				Container				T			
	29-Mar-03	Dry Bulk				Others				O			
	29-Mar-03	Container				Dry Bulk				DB			
	29-Mar-03	Container				Dry Bulk				C8			

	29-Mar-03	Tankers				Tankers				DB			
5	10-Jul-03	Dry Bulk	13.88	13.79	13.97	Container6	13.46	13.37	13.54	C6	13.39	13.3	13.47
	10-Jul-03	Container				Others				O			
	10-Jul-03	Dry Bulk				Dry Bulk				VC			
	10-Jul-03	Dry Bulk				Dry Bulk				DB			
	10-Jul-03	Dry Bulk				Dry Bulk				DB			
	10-Jul-03	VC				Dry Bulk				DB			
	10-Jul-03	Others				VC				DB			
6	07-Oct-03	Tankers	14.42	14.34	14.5	Passengers	14.22	14.14	14.3	P6	14.17	14.08	14.26
	07-Oct-03	Container				Container6				C6			
	07-Oct-03	Passengers				Container6				C8			
	07-Oct-03	Container				Container6				C6			
	07-Oct-03	Container				Container6				C8			
	07-Oct-03	Dry Bulk				Container				C6			
	07-Oct-03	Dry Bulk				Container				T			
	07-Oct-03	Container				Tankers				C6			
	07-Oct-03	Container				Dry Bulk				DB			
	07-Oct-03	Container				Dry Bulk				DB			
7	18-Oct-03	Container	14.35	14.28	14.42	Passengers	14.03	13.96	14.1	P6	14.01	13.93	14.09
	18-Oct-03	Passengers				Container6				C6			
	18-Oct-03	Dry Bulk				Container				C8			
	18-Oct-03	VC				Container				C8			
	18-Oct-03	Others				Container				C8			
	18-Oct-03	Container				Others				O			
	18-Oct-03	Others				Others				O			
	18-Oct-03	VC				Dry Bulk				DB			
	18-Oct-03	Container				VC				VC			
	18-Oct-03	Container				VC				VC			
8	26-Apr-04	Container	14.92	14.84	15.01	Container	14.68	14.6	14.76	C6	14.51	14.43	14.58
	26-Apr-04	Dry Bulk				Container				C8			
	26-Apr-04	Dry Bulk				Container				C6			
	26-Apr-04	Dry Bulk				Container				C6			
	26-Apr-04	Dry Bulk				Dry Bulk				DB			
	26-Apr-04	Dry Bulk				Dry Bulk				DB			
	26-Apr-04	Container				Dry Bulk				DB			
	26-Apr-04	Container				Dry Bulk				DB			
	26-Apr-04	VC				Dry Bulk				VC			
	26-Apr-04	Container				VC				DB			
	26-Apr-04	VC				VC				VC			
9	06-Aug-04	Tankers	13.14	13.04	13.25	Container	12.85	12.76	12.95	C8	12.85	12.76	12.95
	06-Aug-04	VC				Tankers				T			
	06-Aug-04	Dry Bulk				Tankers				T			
	06-Aug-04	Tankers				Tankers				T			
	06-Aug-04	Container				Dry Bulk				DB			

	06-Aug-04	Tankers				VC				VC			
10	13-Sep-04	Tankers	15.64	15.55	15.73	Container6	15.44	15.35	15.52	C6	15.25	15.16	15.33
	13-Sep-04	Others				Container6				C6			
	13-Sep-04	Tankers				Container6				O			
	13-Sep-04	Container				Others				C6			
	13-Sep-04	Others				Others				O			
	13-Sep-04	Container				Others				T			
	13-Sep-04	Dry Bulk				Tankers				O			
	13-Sep-04	Tankers				Tankers				T			
	13-Sep-04	Dry Bulk				Tankers				T			
	13-Sep-04	Others				Tankers				T			
	13-Sep-04	Tankers				Tankers				DB			
	13-Sep-04	Tankers				Dry Bulk				O			
	13-Sep-04	Container				Dry Bulk				DB			

Table C2 Confidence Intervals for Southbound Sample set 1

Sample #1				Confidence Interval					Confidence Interval				Confidence Interval	
Seq #	Transit Date	Data Seq	C_{max} Sim	L	U	LEPT Seq	C_{max} LEPT	L	U	NP Seq	C_{max} NP	L	U
1	02-Nov-02	Container6	6.484	6.457	6.511	Dry Bulk	6.381	6.345	6.417	C6	6.332	6.3	6.364
	02-Nov-02	VC				Dry Bulk				T			
	02-Nov-02	Container6				Tankers				T			
	02-Nov-02	Tankers				Tankers				DB			
	02-Nov-02	Dry Bulk				Container6				DB			
	02-Nov-02	Container6				Container6				C6			
	02-Nov-02	Tankers				Container6				C6			
	02-Nov-02	Dry Bulk				VC				VC			
2	10-Nov-02	Dry Bulk	7.567	7.519	7.615	Dry Bulk	7.427	7.393	7.461	C8	7.374	7.333	7.415
	10-Nov-02	Container				Dry Bulk				T			
	10-Nov-02	Dry Bulk				Dry Bulk				DB			
	10-Nov-02	Dry Bulk				Dry Bulk				DB			
	10-Nov-02	Dry Bulk				Dry Bulk				DB			
	10-Nov-02	Dry Bulk				Dry Bulk				DB			
	10-Nov-02	Dry Bulk				Tankers				DB			
	10-Nov-02	Container				Container				C6			
	10-Nov-02	Container				Container6				DB			
	10-Nov-02	Tankers				Container6				C6			
3	05-Jan-03	Container6	8.149	8.111	8.187	Dry Bulk	7.95	7.918	7.982	C8	7.884	7.849	7.919
	05-Jan-03	Container				Dry Bulk				C8			
	05-Jan-03	Container6				Tankers				T			
	05-Jan-03	Tankers				Tankers				DB			
	05-Jan-03	Container				Tankers				T			
	05-Jan-03	Tankers				Container				DB			
	05-Jan-03	VC				Container				C6			
	05-Jan-03	VC				Container6				T			
	05-Jan-03	Container6				Container6				C6			
	05-Jan-03	Dry Bulk				Container6				C6			
	05-Jan-03	VC				VC				VC			
	05-Jan-03	Tankers				VC				VC			
	05-Jan-03	Dry Bulk				VC				VC			
4	21-May-03	Dry Bulk	6.566	6.531	6.601	Dry Bulk	6.39	6.361	6.419	C8	6.303	6.274	6.332
	21-May-03	Others				Dry Bulk				C8			
	21-May-03	VC				Dry Bulk				DB			
	21-May-03	Container				Container				DB			

	21-May-03	Dry Bulk				Container				DB			
	21-May-03	Container				Others				O			
	21-May-03	Dry Bulk				Container6				C6			
	21-May-03	Container				VC				VC			
5	25-Jun-03	Vehicle Carriers	6.364	6.326	6.402	Tankers	6.151	6.123	6.179	C8	6.132	6.099	6.165
	25-Jun-03	Container				Tankers				C8			
	25-Jun-03	Container6				Container				T			
	25-Jun-03	Container				Container				C6			
	25-Jun-03	VC				Container6				T			
	25-Jun-03	VC				VC				VC			
	25-Jun-03	Tankers				VC				VC			
	25-Jun-03	Tankers				VC				VC			
6	28-Jul-03	Container6	7.886	7.839	7.933	Dry Bulk	7.61	7.573	7.647	T	7.6	7.562	7.638
	28-Jul-03	Dry Bulk				Dry Bulk				DB			
	28-Jul-03	Tankers				Dry Bulk				DB			
	28-Jul-03	VC				Dry Bulk				T			
	28-Jul-03	Dry Bulk				Dry Bulk				DB			
	28-Jul-03	Dry Bulk				Tankers				T			
	28-Jul-03	Tankers				Tankers				DB			
	28-Jul-03	Container6				Tankers				DB			
	28-Jul-03	Dry Bulk				Container6				C6			
	28-Jul-03	Tankers				Container6				C6			
	28-Jul-03	Dry Bulk				VC				VC			
7	24-Sep-03	Others	5.688	5.649	5.727	Container	5.394	5.371	5.417	C8	5.374	5.351	5.397
	24-Sep-03	VC				Others				T			
	24-Sep-03	VC				Tankers				O			
	24-Sep-03	Container				VC				VC			
	24-Sep-03	VC				VC				VC			
	24-Sep-03	Tankers				VC				VC			
8	13-Feb-04	VC	8.035	7.998	8.072	Dry Bulk	7.895	7.861	7.929	C8	7.972	7.937	8.007
	13-Feb-04	Container				Dry Bulk				C8			
	13-Feb-04	Tankers				Dry Bulk				DB			
	13-Feb-04	Container				Dry Bulk				DB			
	13-Feb-04	Dry Bulk				Tankers				T			
	13-Feb-04	VC				Tankers				T			
	13-Feb-04	Others				Tankers				T			
	13-Feb-04	Dry Bulk				Container				DB			
	13-Feb-04	Dry Bulk				Container				DB			
	13-Feb-04	Tankers				Others				O			
	13-Feb-04	Tankers				VC				VC			
	13-Feb-04	Dry Bulk				VC				VC			
9	27-May-04	Tankers	7.695	7.655	7.735	Dry Bulk	7.49	7.455	7.525	C8	7.439	7.402	7.476
	27-May-04	Tankers				Dry Bulk				T			

	27-May-04	Tankers				Tankers				T			
	27-May-04	Dry Bulk				Tankers				T			
	27-May-04	VC				Tankers				DB			
	27-May-04	Others				Tankers				T			
	27-May-04	Dry Bulk				Container				DB			
	27-May-04	Tankers				Others				O			
	27-May-04	Others				Others				O			
	27-May-04	Container				Container6				C6			
	27-May-04	Container				VC				VC			
10	12-Jul-04	Container	7.22	7.188	7.252	Dry Bulk	6.987	6.955	6.987	C8	6.928	6.896	6.96
	12-Jul-04	Tankers				Tankers				C8			
	12-Jul-04	Container				Tankers				T			
	12-Jul-04	VC				Container				C8			
	12-Jul-04	Container				Container				T			
	12-Jul-04	Dry Bulk				Container				DB			
	12-Jul-04	Container				Others				O			
	12-Jul-04	Tankers				Container6				C6			
	12-Jul-04	VC				VC				VC			
	12-Jul-04	Others				VC				VC			

Table C3 Confidence Intervals for Northbound Sample set 2

Sample #2				Confidence Interval				Confidence Interval			Confidence Interval		
Seq #	Transit Date	Data Seq	C_{max} Sim	L	U	LEPT Seq	C_{max} LEPT	L	U	NP Seq	C_{max} NP	L	U
1	12-Dec-02	Container6	14.02	13.94	14.094	Passengers6	13.937	13.86	14.01	P6	13.82	13.74	13.9
	12-Dec-02	Tankers				Container6				C8			
	12-Dec-02	Dry Bulk				Container8				C6			
	12-Dec-02	Others				Tankers				T			
	12-Dec-02	Others				Tankers				O			
	12-Dec-02	Container8				Others				T			
	12-Dec-02	VC				Others				DB			
	12-Dec-02	Tankers				Dry Bulk				O			
	12-Dec-02	Passengers6				VC				VC			
2	19-Feb-03	VC	13.5	13.42	13.585	Container6	13.384	13.31	13.46	C6	13.3	13.21	13.4
	19-Feb-03	General Cargo				Container6				C8			
	19-Feb-03	Container				Container				O			
	19-Feb-03	VC				Others				C6			
	19-Feb-03	Dry Bulk				Others				O			
	19-Feb-03	Container				Dry Bulk				VC			
	19-Feb-03	Container				VC				DB			
	19-Feb-03	Others				VC				VC			
3	22-Apr-03	Passengers	14.3	14.22	14.391	Container6	14.223	14.13	14.31	C8	13.82	13.74	13.9
	22-Apr-03	Tankers				Container8				C6			
	22-Apr-03	VC				Container8				T			
	22-Apr-03	Container				Passengers8				T			
	22-Apr-03	VC				Tankers				P8			
	22-Apr-03	Container				Tankers				T			
	22-Apr-03	Container				Tankers				C6			
	22-Apr-03	Tankers				Tankers				T			
	22-Apr-03	Tankers				VC				VC			
	22-Apr-03	Tankers				VC							
4	24-Jul-03	VC	14.93	14.85	15.012	Container6	14.571	14.49	14.65	C6	14.52	14.44	14.6
	24-Jul-03	VC				Container6				C8			
	24-Jul-03	Others				Container8				C6			
	24-Jul-03	Dry Bulk				Others				O			
	24-Jul-03	Dry Bulk				Others				O			
	24-Jul-03	Dry Bulk				Tankers				DB			
	24-Jul-03	Tankers				Dry Bulk				T			

	24-Jul-03	Container				Dry Bulk				DB		
	24-Jul-03	Container				Dry Bulk				DB		
	24-Jul-03	Others				VC				VC		
	24-Jul-03	Container				VC				VC		
5	10-Sep-03	Container	14.66	14.58	14.742	Container6	14.615	14.54	14.69	C6	14.61	14.53	14.7
	10-Sep-03	Container				Container6				C6			
	10-Sep-03	Others				Container6				C6			
	10-Sep-03	Tankers				Container6				C8			
	10-Sep-03	Others				Container6				T			
	10-Sep-03	Container				Container8				C6			
	10-Sep-03	Others				Others				T			
	10-Sep-03	Tankers				Others				C6			
	10-Sep-03	Container				Others				O			
	10-Sep-03	Container				Tankers				O			
	10-Sep-03	Container				Tankers				O			
6	21-Oct-03	Passengers	14.42	14.34	14.509	Passengers6	14.203	14.12	14.29	P6	14.12	14.03	14.2
	21-Oct-03	Passengers				Container6				P8			
	21-Oct-03	Tankers				Container				C6			
	21-Oct-03	Tankers				Container				C8			
	21-Oct-03	Dry Bulk				Container				T			
	21-Oct-03	VC				Passengers8				C8			
	21-Oct-03	Tankers				Tankers				C8			
	21-Oct-03	Container				Tankers				T			
	21-Oct-03	Container				Tankers				T			
	21-Oct-03	Container				VC				VC			
7	30-Mar-04	Container	13.92	13.84	13.994	Container6	13.785	13.7	13.87	C6	13.71	13.64	13.8
	30-Mar-04	VC				Container6				C8			
	30-Mar-04	Container				Container				C8			
	30-Mar-04	Tankers				Container				T			
	30-Mar-04	Vehicle Carriers				Container				C6			
	30-Mar-04	Container				Tankers				T			
	30-Mar-04	Tankers				Tankers				C8			
	30-Mar-04	Container				VC				VC			
	30-Mar-04	Container				VC				VC			
8	06-May-04	VC	14.69	14.6	14.782	Container6	14.41	14.31	14.51	C6	14.31	14.22	14.4
	06-May-04	Tankers				Container6				C8			
	06-May-04	Dry Bulk				Container				T			
	06-May-04	Dry Bulk				Tankers				C6			
	06-May-04	Tankers				Tankers				T			
	06-May-04	Container				Tankers				T			
	06-May-04	Dry Bulk				Dry Bulk				DB			
	06-May-04	Container				Dry Bulk				DB			
	06-May-04	Container				Dry Bulk				DB			
	06-May-04	Tankers				VC				VC			

9	22-Jun-04	Container	15.09	15.01	15.166	Container6	14.902	14.83	14.97	C6	14.87	14.8	14.9
	22-Jun-04	VC				Container6				C8			
	22-Jun-04	General Cargo				Container				C8			
	22-Jun-04	Tankers				Container				O			
	22-Jun-04	Dry Bulk				Others				T			
	22-Jun-04	Dry Bulk				Others				C6			
	22-Jun-04	VC				Tankers				T			
	22-Jun-04	Container				Tankers				O			
	22-Jun-04	Tankers				Dry Bulk				DB			
	22-Jun-04	Container				Dry Bulk				VC			
	22-Jun-04	Container				VC				DB			
	22-Jun-04	Others				VC				VC			
10	13-Aug-04	Others	14.99	14.9	15.076	Container6	14.656	14.57	14.74	C6	14.75	14.67	14.8
	13-Aug-04	VC				Container6				C8			
	13-Aug-04	Dry Bulk				Container				T			
	13-Aug-04	Dry Bulk				Others				C6			
	13-Aug-04	Others				Others				T			
	13-Aug-04	Container				Tankers				O			
	13-Aug-04	Tankers				Tankers				T			
	13-Aug-04	Tankers				Tankers				O			
	13-Aug-04	Container				Dry Bulk				DB			
	13-Aug-04	Container				Dry Bulk				DB			
	13-Aug-04	Tankers				VC				VC			

Table C4 Confidence Intervals for Southbound Sample set 2

Sample #2				Confidence Interval				Confidence Interval			Confidence Interval		
Seq #	Transit Date	Data Seq	C_{max} Sim	L	U	LEPT Seq	C_{max} LEPT	L	U	NP Seq	C_{max} NP	L	U
1	03-Oct-02	VC	6.297	6.26	6.33	Dry Bulk	6.284	6.24	6.33	C8	6.211	6.18	6.242
	03-Oct-02	Tankers				Dry Bulk				C6			
	03-Oct-02	Container				Tankers				T			
	03-Oct-02	Dry Bulk				Container				DB			
	03-Oct-02	Container6				Container6				DB			
	03-Oct-02	Dry Bulk				Container6				VC			
	03-Oct-02	Container6				VC				C6			
	03-Oct-02	VC				VC				VC			
2	15-Nov-02	Container6	7.512	7.48	7.55	Dry Bulk	7.43	7.39	7.47	T	7.428	7.392	7.464
	15-Nov-02	Container				Dry Bulk				DB			
	15-Nov-02	Tankers				Dry Bulk				C8			
	15-Nov-02	Container				Tankers				DB			
	15-Nov-02	Container				Container				DB			
	15-Nov-02	Container6				Container				C8			
	15-Nov-02	VC				Container				C6			
	15-Nov-02	Dry Bulk				Container6				C6			
	15-Nov-02	Dry Bulk				Container6				C6			
	15-Nov-02	Dry Bulk				Container6				C8			
	15-Nov-02	Container6				VC				VC			
3	18-Mar-03	Vehicle Carriers	6.382	6.34	6.42	Dry Bulk	6.231	6.2	6.26	C8	6.173	6.141	6.205
	18-Mar-03	Container6				Dry Bulk				DB			
	18-Mar-03	Container				Dry Bulk				DB			
	18-Mar-03	Dry Bulk				Container				C6			
	18-Mar-03	VC				Container6				S			
	18-Mar-03	VC				VC				VC			
	18-Mar-03	Dry Bulk				VC				VC			
	18-Mar-03	Dry Bulk				VC				VC			
4	30-May-03	VC	6.933	6.9	6.97	Dry Bulk	6.869	6.84	6.9	C8	6.823	6.792	6.854
	30-May-03	Tankers				Dry Bulk				T			
	30-May-03	Container				Tankers				DB			
	30-May-03	Container6				Tankers				T			
	30-May-03	Container				Tankers				DB			
	30-May-03	Dry Bulk				Container				T			
	30-May-03	Tankers				Container				C6			

	30-May-03	Tankers				Container6				C8			
	30-May-03	Dry Bulk				VC				VC			
5	03-Jul-03	VC	7.916	7.87	7.96	Dry Bulk	7.704	7.67	7.74	C8	6.823	6.788	6.858
	03-Jul-03	Tankers				Tankers				C8			
	03-Jul-03	VC				Tankers				T			
	03-Jul-03	Container				Tankers				T			
	03-Jul-03	Container				Tankers				T			
	03-Jul-03	Others				Container				DB			
	03-Jul-03	Container6				Container				T			
	03-Jul-03	Dry Bulk				Others				O			
	03-Jul-03	Tankers				Others				O			
	03-Jul-03	Others				Container6				C6			
	03-Jul-03	Tankers				VC				VC			
	03-Jul-03	Tankers				VC				VC			
6	14-Nov-03	Container6	6.771	6.74	6.8	Dry Bulk	6.645	6.62	6.67	C8	6.567	6.539	6.595
	14-Nov-03	Container				Dry Bulk				C8			
	14-Nov-03	Others				Container				DB			
	14-Nov-03	Container				Container				DB			
	14-Nov-03	VC				Container				C6			
	14-Nov-03	Dry Bulk				Others				C8			
	14-Nov-03	Dry Bulk				Others				O			
	14-Nov-03	Others				Container6				O			
	14-Nov-03	Container				VC				VC			
7	19-Dec-03	Tankers	7.862	7.82	7.9	Dry Bulk	7.647	7.61	7.68	C8	7.583	7.543	7.623
	19-Dec-03	Container				Dry Bulk				C8			
	19-Dec-03	Container				Tankers				DB			
	19-Dec-03	Container				Tankers				T			
	19-Dec-03	Container				Tankers				DB			
	19-Dec-03	Dry Bulk				Tankers				T			
	19-Dec-03	Tankers				Container				T			
	19-Dec-03	Container				Container				T			
	19-Dec-03	Dry Bulk				Container6				C6			
	19-Dec-03	Tankers				Container6				C6			
	19-Dec-03	Tankers				Container6				C6			
8	30-Jan-04	Container	7.672	7.63	7.71	Dry Bulk	7.701	7.66	7.7	C8	7.643	7.604	7.643
	30-Jan-04	Container				Dry Bulk				C8			
	30-Jan-04	Dry Bulk				Dry Bulk				DB			
	30-Jan-04	Dry Bulk				Dry Bulk				DB			
	30-Jan-04	Container				Dry Bulk				DB			
	30-Jan-04	Dry Bulk				Dry Bulk				DB			
	30-Jan-04	Dry Bulk				Container				O			
	30-Jan-04	Dry Bulk				Container				DB			
	30-Jan-04	Dry Bulk				Others				O			
	30-Jan-04	Others				Container6				C6			
	30-Jan-04	Container				Container6				C6			

9	19-Apr-04	Container6	7.175	7.14	7.21	Dry Bulk	7.169	7.14	7.2	C6	7.139	7.102	7.176
	19-Apr-04	Container6				Tankers				T			
	19-Apr-04	Tankers				Tankers				T			
	19-Apr-04	Tankers				Tankers				DB			
	19-Apr-04	Container6				Tankers				T			
	19-Apr-04	Dry Bulk				Container6				C6			
	19-Apr-04	Tankers				Container6				T			
	19-Apr-04	Container6				Container6				C6			
	19-Apr-04	Tankers				Container6				C6			
	19-Apr-04	Container6				Container6				C6			
10	10-Jun-04	Tankers	8.716	8.67	8.76	Tankers	8.38	8.34	8.42	C8	8.278	8.241	8.315
	10-Jun-04	Container				Tankers				C8			
	10-Jun-04	Container				Tankers				T			
	10-Jun-04	Container				Tankers				T			
	10-Jun-04	Container6				Tankers				T			
	10-Jun-04	VC				Container				T			
	10-Jun-04	Tankers				Container				T			
	10-Jun-04	Others				Container				C6			
	10-Jun-04	VC				Others				C8			
	10-Jun-04	Others				Others				C6			
	10-Jun-04	Tankers				Container6				O			
	10-Jun-04	Tankers				Container6				VC			
	10-Jun-04	Container6				VC				O			
	10-Jun-04	Tankers				VC				VC			

APPENDIX D

Performance Comparison for Northbound using PM Locks

Table D1 Performance Comparison PM Locks

	PM seq	Makespan	SEPT	Makespan	LEPT	Makespan	S-L1	Makespan	S-L2	Makespan
1	T	13.988	VC	14.179	C8	13.985	VC	13.924	VC	14.012
	C6		2 P6		O		C6		P6	
	DB		3 C6		O		T		C6	
	O		4 DB		T		O		DB	
	O		5 T		T		C8		T	
	C8		6 T		DB		O		C8	
	VC		7 O		C6		T		O	
	T		8 O		P6		DB		O	
	P6		9 C8		VC		P6		T	
2	VC	13.285	VC	13.672	C8	13.495	VC	13.53	VC	13.41
	O		2 VC		O		C6		VC	
	DB		3 C6		O		DB		C6	
	VC		4 C6		DB		O		C6	
	C6		5 DB		C6		C8		C8	
	C6		6 O		C6		O		O	
	C8		7 O		VC		C6		O	
	O		8 C8		VC		VC		DB	
3	T	14.387	VC	14.332	C8	14.082	VC	14.207	VC	14.234
	VC		2 VC		C8		C6		VC	
	C6		3 C6		T		T		C6	
	VC		4 P8		T		T		P8	
	C8		5 T		T		C8		T	
	C8		6 T		T		C8		C8	
	T		7 T		P8		T		C8	
	T		8 T		C6		T		T	
	T		9 C8		VC		P8		T	
	P8		10 C8		VC		VC		T	
4	O	14.53	VC	14.863	C8	14.654	VC	14.803	VC	14.681
	DB		2 VC		O		C6		VC	
	DB		3 C6		O		DB		C6	
	DB		4 C6		T		DB		C6	
	T		5 DB		DB		O		DB	
	C6		6 DB		DB		C8		C8	

	C6		7 DB		DB		O		O	
	O		8 T		C6		T		O	
	C8		9 O		C6		DB		T	
	VC		10 O		VC		C6		DB	
	VC		11 C8		VC		VC		DB	
5	T	14.387	C6	14.388	C8	14.742	C6	14.268	C6	14.212
	O		2 C6		O		C6		C6	
	C6		3 C6		O		C6		C6	
	O		4 C6		T		T		C6	
	T		5 C6		T		O		C6	
	C6		6 T		C6		C8		C8	
	C8		7 T		C6		O		O	
	C6		8 O		C6		T		O	
	C6		9 O		C6		C6		T	
	C6		10 C8		C6		C6		T	
6	P8	14.332	VC	14.473	C8	14.12	VC	14.402	VC	14.386
	VC		2 P6		C8		C6		P6	
	T		3 C6		T		DB		C6	
	DB		4 P8		T		T		P8	
	C6		5 DB		T		C8		DB	
	C8		6 T		DB		C8		C8	
	C8		7 T		P8		T		C8	
	P6		8 T		C6		T		T	
	T		9 C8		P6		P8		T	
	T		10 C8		VC		P6		T	
7	C6	13.783	VC	13.877	C8	13.687	VC	13.786	VC	13.804
	T		2 VC		C8		C6		VC	
	VC		3 C6		C8		T		C6	
	C6		4 C6		T		C8		C6	
	T		5 T		T		C8		T	
	C8		6 T		C6		C8		C8	
	C8		7 C8		C6		T		C8	
	C8		8 C8		VC		C6		C8	
	VC		9 C8		VC		VC		T	
8	DB	14.978	VC	14.642	C8	14.397	VC	14.586	VC	14.551
	T		2 C6		T		C6		C6	
	DB		3 C6		T		DB		C6	
	C6		4 DB		T		T		DB	
	C8		5 DB		DB		T		DB	
	C6		6 DB		DB		C8		C8	
	T		7 T		DB		T		T	

	VC		8 T		C6		DB		T	
	T		9 T		C6		DB		T	
	DB		10 C8		VC		C6		DB	
9	DB	15.592	VC	15.14	C8	14.89	VC	15.047	VC	15.249
	DB		2 VC		C8		C6		VC	
	T		3 C6		O		DB		C6	
	VC		4 C6		O		T		C6	
	C6		5 DB		T		O		DB	
	T		6 DB		T		C8		DB	
	C6		7 T		DB		C8		T	
	C8		8 T		DB		O		T	
	O		9 O		C6		T		O	
	C8		10 O		C6		DB		O	
	VC		11 C8		VC		C6		C8	
	O		12 C8		VC		VC		C8	
10	DB	15.186	VC	14.95	C8	14.7	VC	14.849	VC	14.922
	DB		2 C6		O		C6		C6	
	O		3 C6		O		DB		C6	
	T		4 DB		T		T		DB	
	C6		5 DB		T		O		DB	
	T		6 T		T		C8		T	
	C8		7 T		DB		O		C8	
	C6		8 T		DB		T		O	
	T		9 O		C6		T		O	
	O		10 O		C6		DB		T	
	VC		11 C8		VC		C6		T	

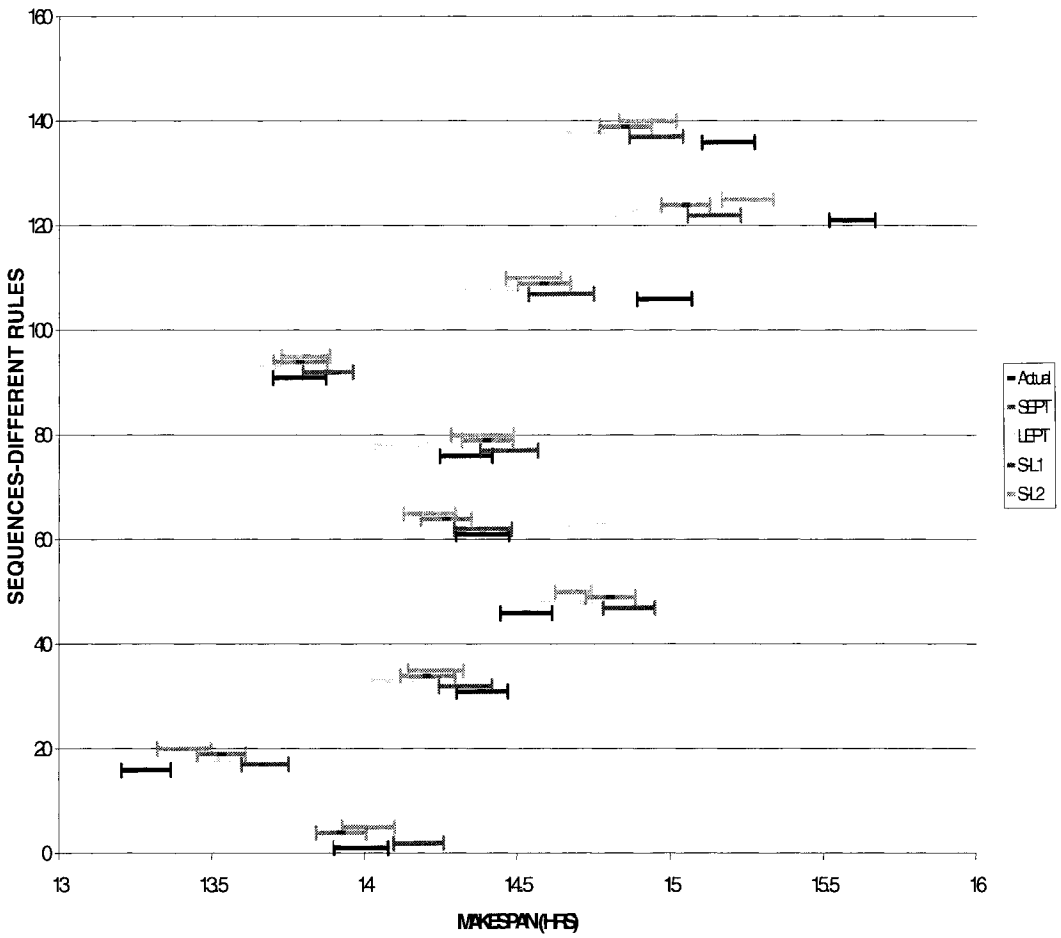

Figure D1 Confidence Intervals for Northbound using PM Locks as the bottleneck

Appendix E

Performance Comparison for Northbound and Southbound with different rules

Table E 1 Northbound- Sample set 1

Set #	Historical Data (Simulation) Seq			LEPT Seq			SEPT Seq			S-L1 Seq			S-L2 Seq		
1	DB			VC			C6			C6			C6		
	C8			T			C6			C6			C6		
	DB			DB			C6			C8			C6		
	C8			DB			C6			DB			C6		
	DB			DB			C8			T			VC		
	C8			C8			DB			VC			T		
	T			C6			DB			DB			DB		
	C8			C6			DB			DB			DB		
	C8			C6			T			C6			DB		
	VC	0.09		C6			VC			C6			C8		
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.	
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	14.81	14.72	14.91	14.52	14.43	14.6	14.23	14.15	14.31	14.4	14.3	14.5	14.54	14.5	14.6
2	DB			O			C6			C6			C6		
	DB			O			C8			C8			C8		
	O			DB			C8			C8			C8		
	C8			DB			C8			DB			C8		
	C8			C8			DB			O			DB		
	C8			C8			DB			O			O		
	C8			C8			O			DB			O		
	O			C6			O			C8			DB		
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.	
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	14.14	14.06	14.22	13.89	13.81	13.96	13.64	13.57	13.72	13.87	13.8	13.9	13.7	13.6	13.8
3	DB			VC			C8			C8			C8		
	VC			VC			DB			DB			DB		
	DB			VC			DB			VC			DB		
	DB			DB			DB			VC			DB		
	C8			DB			VC			VC			VC		
	VC			DB			VC			DB			VC		
	VC			C8			VC			DB			VC		
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.	
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	13.68	13.6	13.76	13.36	13.28	13.43	13.32	13.23	13.4	13.38	13.3	13.5	13.32	13.2	13.4
4	C8			T			C6			C6			C6		
	O			O			C6			C8			C6		
	DB			DB			C8			DB			C8		
	DB			DB			DB			T			DB		
	C8			C8			DB			O			T		

	C8			C6			O			DB			O	
	T			C6			T			C6			DB	
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	13.43	13.34	13.52	13.54	13.45	13.63	13.362	13.27	13.45	13.44	13.3	13.5	13.39	13.3	13.5
5	DB			VC			C6			C6			C6		
	C8			O			DB			DB			DB		
	DB			DB			DB			DB			DB		
	DB			DB			DB			VC			DB		
	DB			DB			DB			O			VC		
	VC			DB			O			DB			O		
	O			C6			VC			DB			DB		
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	13.88	13.79	13.97	13.54	13.45	13.62	13.455	13.37	13.54	13.72	13.6	13.8	13.68	13.6	13.8
6	T			T			P6			P6			P6		
	C8			DB			C6			C6			C6		
	P6			DB			C6			C6			C6		
	C8			C8			C6			C8			C6		
	C8			C8			C6			DB			C6		
	DB			C6			C8			T			T		
	DB			C6			C8			DB			DB		
	C8			C6			DB			C8			DB		
	C8			C6			DB			C6			C8		
	C8			P6			T			C6			C8		
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	14.42	14.34	14.5	14.57	14.48	14.66	14.218	14.14	14.3	14.29	14.2	14.4	14.33	14.2	14.4
7	C8			VC			P6			P6			P6		
	P6			VC			C6			C8			C6		
	DB			DB			C8			C8			C8		
	VC			O			C8			O			C8		
	O			O			C8			VC			C8		
	C8			C8			O			VC			VC		
	O			C8			O			DB			VC		
	VC			C8			DB			O			DB		
	C8			C6			VC			C8			O		
	C8			P6			VC			C6			O		
	C_{max}	95% C.I.			C.I.			C.I.			C.I.			C.I.
		L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U	C_{max}	L	U
	14.35	14.28	14.42	14.27	14.19	14.34	14.03	13.96	14.1	14.14	14.1	14.2	14.15	14.1	14.2
8	C8			VC			C6			C6			C6		
	DB			VC			C6			C6			C6		
	DB			DB			C6			DB			C6		
	DB			DB			C8			DB			C8		
	DB			DB			DB			DB			DB		
	DB			DB			DB			VC			DB		
	C8			DB			DB			VC			VC		

	C8			C88			DB			DB			VC	
	VC			C6			DB			DB			DB	
	C8			C6			VC			C8			DB	
	VC			C6			VC			C6			DB	
	C_{max}	**95% C.I.**			**C.I.**			**C.I.**			**C.I.**			**C.I.**
		L	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**
	14.92	14.84	15.01	14.85	14.77	14.94	14.68	14.6	14.76	14.95	14.9	15	14.78	14.7	14.9
9	T			VC			C8			C8			C8	
	VC			DB			T			T			T	
	DB			T			T			DB			T	
	T			T			T			VC			VC	
	C8			T			DB			T			DB	
	T			C8			VC			T			T	
	C_{max}	**95% C.I.**			**C.I.**			**C.I.**			**C.I.**			**C.I.**
		L	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**
	13.14	13.04	13.25	13.35	13.25	13.46	12.85	12.76	12.95	13.09	13	13.2	13	12.9	13.1
10	T			T			C6			C6			C6	
	O			T			C6			C6			C6	
	T			T			C6			O			C6	
	C8			T			O			O			O	
	O			T			O			DB			O	
	C8			DB			O			T			O	
	DB			DB			DB			T			T	
	T			O			DB			T			T	
	DB			O			T			T			T	
	O			O			T			T			T	
	T			C6			T			DB			T	
	T			C6			T			O			DB	
	C8			C6			T			C6			DB	
	C_{max}	**95% C.I.**			**C.I.**			**C.I.**			**C.I.**			**C.I.**
		L	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**	C_{max}	**L**	**U**
	15.64	15.55	15.73	15.65	15.56	15.74	15.44	15.35	15.52	15.62	15.5	15.7	15.5	15.4	15.6

Table E2 Southbound- Sample set 1

Seq #	Data Sequence	Cmax Sim	C.I. L	C.I. U	LEPT Sequence	Cmax LEPT	C.I. L	C.I. U	SEPT Sequence	Cmax SEPT	C.I. L	C.I. U	S-L1	Cmax S-L1	C.I. L	C.I. U	S-L2	Cmax S-L2	C.I. L	C.I. U
1	C6	6.484	6.46	6.51	DB	6.381	6.35	6.42	VC	6.444	6.41	6.47	VC	6.347	6.35	6.49	VC	6.485	6.45	6.52
	VC				DB				C6				C6				C6			
	C6				T				C6				T				C6			
	T				T				C6				DB				C6			
	DB				C6				T				DB				DB			
	C6				C6				T				T				DB			
	T				C6				DB				C6				T			
	DB				VC				DB				VC				T			
2	DB	7.567	7.52	7.62	DB	7.427	7.39	7.46	C6	7.441	7.4	7.48	C6	7.408	7.37	7.45	C6	7.441	7.4	7.48
	C8				DB				C6				C8				C6			
	DB				DB				C8				DB				C8			
	DB				DB				T				DB				T			
	DB				DB				DB				DB				DB			
	DB				DB				DB				DB				DB			
	DB				T				DB				DB				DB			
	C8				C8				DB				DB				DB			
	C8				C6				DB				T				DB			
	T				C6				DB				C6				DB			
3	C6	8.162	8.11	8.19	DB	7.95	7.92	7.98	VC	8.052	8.01	8.1	VC	7.874	7.84	7.9	VC	7.998	7.96	7.03
	C8				DB				VC				VC				VC			
	C6				T				VC				C6				VC			
	T				T				C6				C8				C6			
	C8				T				C6				T				C6			
	T				C8				C6				T				C6			
	VC				C8				C8				DB				C8			
	VC				C6				C8				DB				DB			
	C6				C6				T				T				DB			
	DB				C6				T				C8				T			
	VC				VC				T				C6				T			
	T				VC				DB				C6				T			
	DB				VC				DB				VC				C8			
4	DB	6.559	6.53	6.6	DB	6.39	6.37	6.42	VC	6.478	6.44	6.51	VC	6.386	6.35	6.42	VC	6.494	6.46	6.53
	O				DB				C6				O				C6			
	VC				DB				O				C8				O			
	C8				C8				C8				DB				C8			
	DB				C8				C8				DB				DB			
	C8				O				DB				DB				DB			
	DB				C6				DB				C8				DB			
	C8				VC				DB				C6				C8			

5	VC	6.364	6.33	6.4	T	6.151	6.12	6.18	VC	6.268	6.23	6.3	VC	6.092	6.05	6.11	VC	6.19	6.16	6.22
	C8				T				VC				VC				VC			
	C6				C8				VC				C8				VC			
	C8				C8				C6				T				C6			
	VC				C6				C8				T				T			
	VC				VC				C8				C8				T			
	T				VC				T				C6				C8			
	T				VC				T				VC				C8			
6	C6	7.886	7.84	7.93	DB	7.61	7.57	7.65	VC	7.7	7.66	7.74	VC	7.697	7.66	7.74	VC	7.78	7.74	7.82
	DB				DB				C6				C6				C6			
	T				DB				C6				T				C6			
	VC				DB				T				DB				T			
	DB				DB				T				DB				T			
	DB				T				T				DB				DB			
	T				T				DB				DB				DB			
	C6				T				DB				DB				DB			
	DB				C6				DB				T				DB			
	T				C6				DB				T				DB			
	DB				VC				DB				C6				T			
7	VC	5.688	5.65	5.73	C8	5.394	5.37	5.42	VC	5.514	5.48	5.55	VC	5.387	5.36	5.42	VC	5.512	5.48	5.55
	VC				T				VC				VC				VC			
	C8				VC				VC				C8				VC			
	VC				VC				T				T				C8			
	T				VC				C8				VC				T			
8	VC				DB				VC				VC				VC			
	C8	8.035	8	8.07	DB	7.895	7.86	7.93	VC	7.966	7.93	8.01	O	7.882	7.85	7.92	VC	8.028	7.99	7.07
	T				DB				O				C8				O			
	C8				DB				C8				T				C8			
	DB				T				C8				DB				C8			
	VC				T				T				DB				T			
	O				T				T				DB				DB			
	DB				C8				T				DB				DB			
	DB				C8				DB				T				DB			
	T				O				DB				T				DB			
	T				VC				DB				C8				T			
	DB				VC				DB				VC				T			
9	T				DB				VC				VC	7.538	7.5	7.58	VC	7.707	7.67	7.75
	T	7.695	7.66	7.74	DB	7.49	7.46	7.53	C6	7.601	7.57	7.64	O				C6			
	T				T				O				C8				O			
	DB				T				O				T				O			
	VC				T				C8				T				C8			
	O				T				T				DB				T			
	DB				C8				T				DB				DB			

	T			O			T			T			DB	
	O			O			T			T			T	
	C8			C6			DB			O			T	
	C8			VC			DB			C6			T	
10	C8			DB			VC		7.071	7.04	7.11	VC	6.915	6.89	6.94	VC	7.024	6.99	7.06
	T	7.22	7.19	7.25	T	6.987	6.96	6.99	VC			C6				VC			
	C8				T				C6			C8				C6			
	VC				C8				O			C8				O			
	C8				C8				C8			T				C8			
	DB				C8				C8			DB				DB			
	C8				O				C8			T				T			
	T				C6				T			C8				T			
	VC				VC				T			O				C8			
	O				VC				DB			VC				C8			

Table E3 Northbound- Sample set 2

Sample #2			C.I.				C.I.				C.I.				C.I.				C.I.	
Seq #	Data Seq	Cmax Sim	L	U	LEPT Seq	Cmax LEPT	L	U	SEPT Seq	Cmax SEPT	L	U	S-L1	Cmax S-L1	L	U	S-L2	C max S-L2	L	U
1	C6	14.016	13.9	14.1	VC	14.052	14	14.1	P6	13.937	13.86	14.01	P6	13.934	13.85	14.02	P6	13.954	13.87	14.04
	T				T				C6				C8				C6			
	DB				T				C8				O				C8			
	O				DB				O				T				DB			
	O				O				O				VC				VC			
	C8				O				DB				T				T			
	VC				C8				T				O				T			
	T				C6				T				DB				O			
	P6				P6				VC				C6				O			
2	VC	13.504	13.4	13.6	VC	13.6	13.5	13.7	C6	13.384	13.31	13.46	C6	13.634	13.56	13.71	C6	13.517	13.43	13.6
	General Cargo				VC				C6				C8				C6			
	C6				DB				C8				O				C8			
	VC				O				O				VC				DB			
	DB				O				O				VC				VC			
	C6				C8				DB				DB				VC			
	C8				C6				VC				O				O			
	O				C6				VC				C6				O			
3	T	14.303	14.2	14.4	VC	14.307	14.2	14.4	C6	14.223	14.13	14.31	C6	14.379	14.29	14.47	C6	14.297	14.21	14.38
	VC				VC				C8				C8				C8			
	C6				T				C8				T				C8			
	VC				T				P8				T				P8			
	C8				T				T				VC				T			
	C8				T				T				VC				VC			
	T				P8				T				T				VC			
	T				C8				T				T				T			
	T				C8				VC				P8				T			
	P8				C6				VC				C8				T			
4	O	14.931	14.9	15	VC				C6	14.571	14.49	14.65	C6				C6			
	DB				VC				C6				C8				C6			
	DB				T				C8				DB				C8			
	DB				DB				O				O				O			
	T				DB				O				T				O			
	C6				DB				DB				VC				VC			
	C6				O				DB				VC				VC			
	O				O				DB				O				T			
	C8				C8				T				DB				DB			

				VC				VC			DB	DB
				VC				VC			C6	DB
5	C6	14.66	14.6	14.7	T	C6	14.615	14.54	14.69	C6	C6
	O				T	C6				C6	C6
	T				O	C6				C6	C6
	O				O	C6				C8	C6
	C6				O	C6				O	C6
	O				C8	C8				T	C8
	T				C6	O				T	O
	C6				C6	O				O	O
	C8				C6	O				O	O
	C6				C6	T				C6	T
	C6				C6	T				C6	T
6	P8	14.423	14.3	14.5	VC	P6	14.203	14.12	14.29	P6	P6
	T				T	C6				C8	C6
	T				T	C8				C8	C8
	DB				T	C8				P8	C8
	VC				P8	C8				T	C8
	T				C8	P8				T	VC
	C8				C8	T				VC	T
	C8				C8	T				T	T
	C8				C6	T				C8	T
	P6				P6	VC				C6	P8
7	C6	13.916	13.8	14	VC	C6	13.785	13.7	13.87	C6	C6
	T				VC	C6				C8	C6
	VC				T	C8				C8	C8
	C6				T	C8				T	C8
	T				C8	C8				VC	C8
	C8				C8	T				VC	T
	C8				C8	T				T	T
	C8				C6	VC				C8	VC
	VC				C6	VC				C6	VC
8	DB	14.689	14.6	14.8	VC	C6	14.41	14.31	14.51	C6	C6
	T				T	C6				C8	C6
	DB				T	C8				DB	C8
	C6				T	DB				T	DB
	C8				DB	DB				T	DB
	C6				DB	DB				VC	VC
	T				DB	T				T	T
	VC				C8	T				DB	T
	T				C6	T				DB	T
	DB				C6	VC				C6	DB
9	DB	15.086	15	15.2	VC	C6	14.902	14.83	14.97	C6	C6

	DB			VC	C6			C8	C6
	T			T	C8			DB	C8
	VC			T	C8			O	C8
	C6			O	DB			T	DB
	T			O	DB			VC	DB
	C6			DB	O			VC	VC
	C8			DB	O			T	VC
	O			C8	T			O	T
	C8			C8	T			DB	T
	VC			C6	VC			C8	O
	O			C6	VC			C6	O
10	DB	14.989	14.9	15.1 VC	C6	14.656	14.57	14.74 C6	C6
	DB			T	C6			C8	C6
	O			T	C8			DB	C8
	C6			T	DB			O	DB
	T			O	DB			T	DB
	T			O	O			T	O
	C8			DB	O			VC	VC
	C6			DB	T			T	T
	T			C8	T			O	T
	O			C6	T			DB	T
	VC			C6	VC			C6	O

Table E4 Southbound- Sample set 2

Sample #2			C.I.				C.I.				C.I.				C.I.				C.I.	
Seq #	Data Seq	Cmax Sim	L	U	LEPT Seq	Cmax LEPT	L	U	SEPT Seq	Cmax SEPT	L	U	S-L1	Cmax S-L1	L	U	S-L2	C max S-L2	L	U
1	VC	6.297	6.263	6.331	DB	6.284	0.044	12.52	VC	6.325	6.291	6.359	VC	6.275	6.24	6.309	VC	6.314	6.282	6.346
	T				DB				VC				C6				VC			
	C8				T				C6				C8				C6			
	DB				C8				C6				DB				C6			
	C6				C6				C8				DB				DB			
	DB				C6				T				T				DB			
	C6				VC				DB				C6				T			
	VC				VC				DB				VC				C8			
2	C6	7.512	7.475	7.549	DB	7.43	7.43	7.43	VC	7.51	7.469	7.55	VC	7.44	7.408	7.471	VC	7.528	7.493	7.563
	C8				DB				C6				C6				C6			
	T				DB				C6				C8				C6			
	C8				T				C6				C8				C6			
	C8				C8				C8				DB				C8			
	C6				C8				C8				DB				C8			
	VC				C8				C8				DB				DB			
	DB				C6				T				T				DB			
	DB				C6				DB				C8				DB			
	DB				C6				DB				C6				T			
	C6				VC				DB				C6				C8			
3	VC	6.382	6.344	6.42	DB	6.231	6.231	6.231	VC	6.273	6.238	6.308	VC	6.234	6.2	6.257	VC	6.264	6.198	6.261
	C6				DB				VC				VC				VC			
	C8				DB				VC				C8				VC			
	DB				C8				C6				DB				C6			
	VC				C6				C8				DB				DB			
	VC				VC				DB				DB				DB			
	DB				VC				DB				C6				DB			
	DB				VC				DB				VC				C8			
4	VC	6.933	6.896	6.97	DB	6.869	6.869	6.869	VC	6.93	6.894	6.965	VC	6.882	6.845	6.918	VC	6.971	6.931	7.011
	T				DB				C6				C8				C6			
	C8				T				C8				T				C8			
	C6				T				C8				T				C8			
	C8				T				T				DB				T			
	DB				C8				T				DB				DB			
	T				C8				T				T				DB			
	T				C6				DB				C8				T			
	DB				VC				DB				C6				T			

5	VC	7.916	7.874	7.958	DB	7.704	7.704	7.704	VC	8.2	8.161	8.239	VC	7.716	7.68	7.75	VC	7.795	7.758	7.831
	T				T				VC				C6				VC			
	VC				T				C6				O				C6			
	C8				T				O				C8				O			
	C8				T				O				T				O			
	O				C8				C8				T				C8			
	C6				C8				C8				DB				DB			
	DB				O				T				T				T			
	T				O				T				T				T			
	O				C6				T				C8				T			
	T				VC				T				O				T			
	T				VC				DB				VC				C8			
6	C6	6.771	6.739	6.803	DB	6.645	6.645	6.645	VC	6.749	6.713	6.785	VC	6.688	6.647	6.716	VC	6.762	6.73	6.795
	C8				DB				C6				O				C6			
	O				C8				O				C8				O			
	C8				C8				O				C8				O			
	VC				C8				C8				DB				C8			
	DB				O				C8				DB				DB			
	DB				O				C8				C8				DB			
	O				C6				DB				O				C8			
	C8				VC				DB				C6				C8			
7	T	7.862	7.821	7.903	DB	7.647	7.647	7.647	C6	7.713	6.675	6.751	C6	7.644	7.604	7.684	C6	7.799	7.763	7.834
	T				DB				C6				C6				C6			
	T				T				C6				C8				C6			
	C8				T				C8				T				C8			
	C8				T				C8				T				C8			
	C6				T				T				DB				DB			
	C6				C8				T				DB				DB			
	DB				C8				T				T				T			
	T				C6				T				T				T			
	C6				C6				DB				C8				T			
	DB				C6				DB				C6				T			
8	O	7.672	7.634	7.71	DB	7.701	7.701	7.701	C6	7.729	7.689	7.77	C6	7.694	7.653	7.739	C6	7.729	7.689	7.77
	C6				DB				C6				O				C6			
	C8				DB				O				C8				O			
	C8				DB				C8				DB				C8			
	DB				DB				C8				DB				C8			
	DB				DB				DB				DB				DB			
	C6				C8				DB				DB				DB			
	DB				C8				DB				DB				DB			
	DB				O				DB				DB				DB			
	DB				C6				DB				C8				DB			
	DB				C6				DB				C6				DB			

9	C6	7.175	7.142	7.208	DB	7.169	7.169	7.169	C6	7.266	7.227	7.304	C6	7.231	7.194	7.267	C6	7.323	7.284	7.363
	C6				T				C6				C6				C6			
	T				T				C6				C6				C6			
	T				T				C6				T				C6			
	C6				T				C6				T				C6			
	DB				C6				T				DB				DB			
	T				C6				T				T				T			
	C6				C6				T				T				T			
	T				C6				T				C6				T			
	C6				C6				DB				C6				T			
10	T	8.716	8.672	8.76	T	8.38	0.972	15.79	VC	8.524	8.485	8.564	VC	8.304	8.266	8.342	VC	8.442	8.404	8.481
	C8				T				VC				C6				VC			
	C8				T				C6				O				C6			
	C8				T				C6				C8				C6			
	C6				T				O				C8				O			
	VC				C8				O				T				O			
	T				C8				C8				T				C8			
	O				C8				C8				T				T			
	VC				O				C8				T				T			
	O				O				T				T				T			
	T				C6				T				C8				T			
	T				C6				T				O				T			
	C6				VC				T				C6				C8			
	T				VC				T				VC				C8			

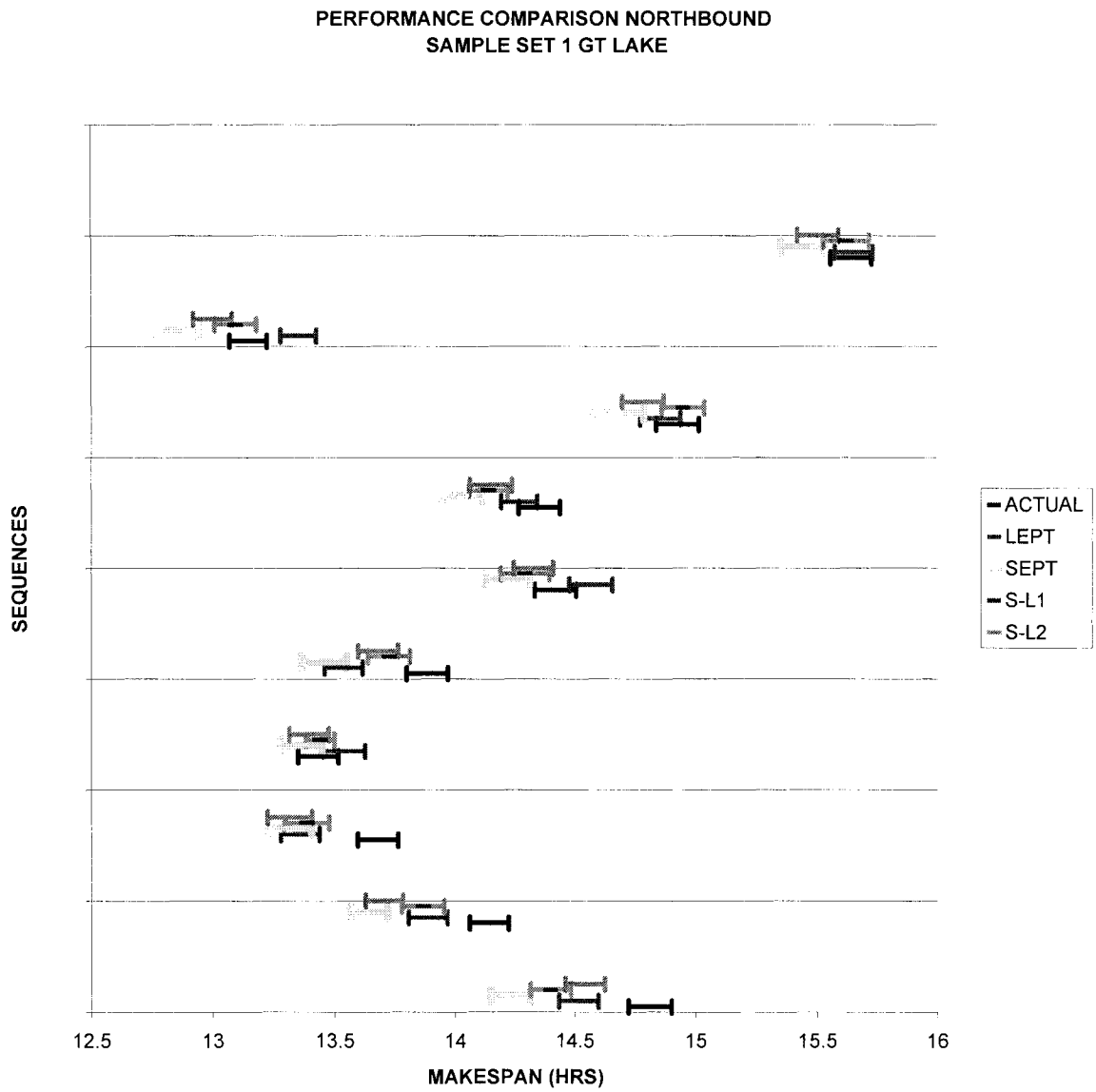

Figure E1 Confidence intervals for Northbound sample set 1 GT Lake. Different Rules Comparison

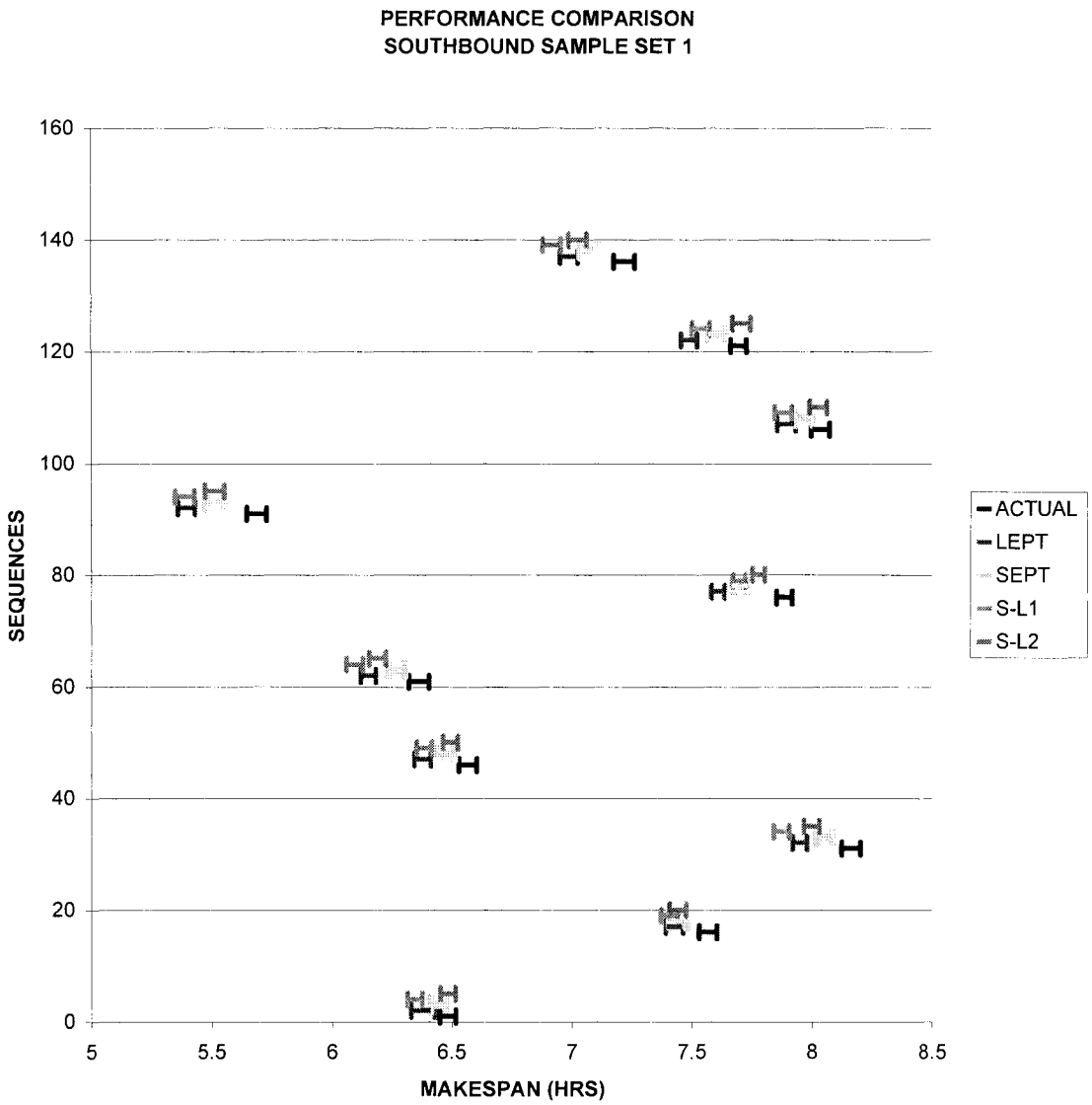

Figure E2 Confidence intervals for Southbound sample set 1. Different Rules Comparison

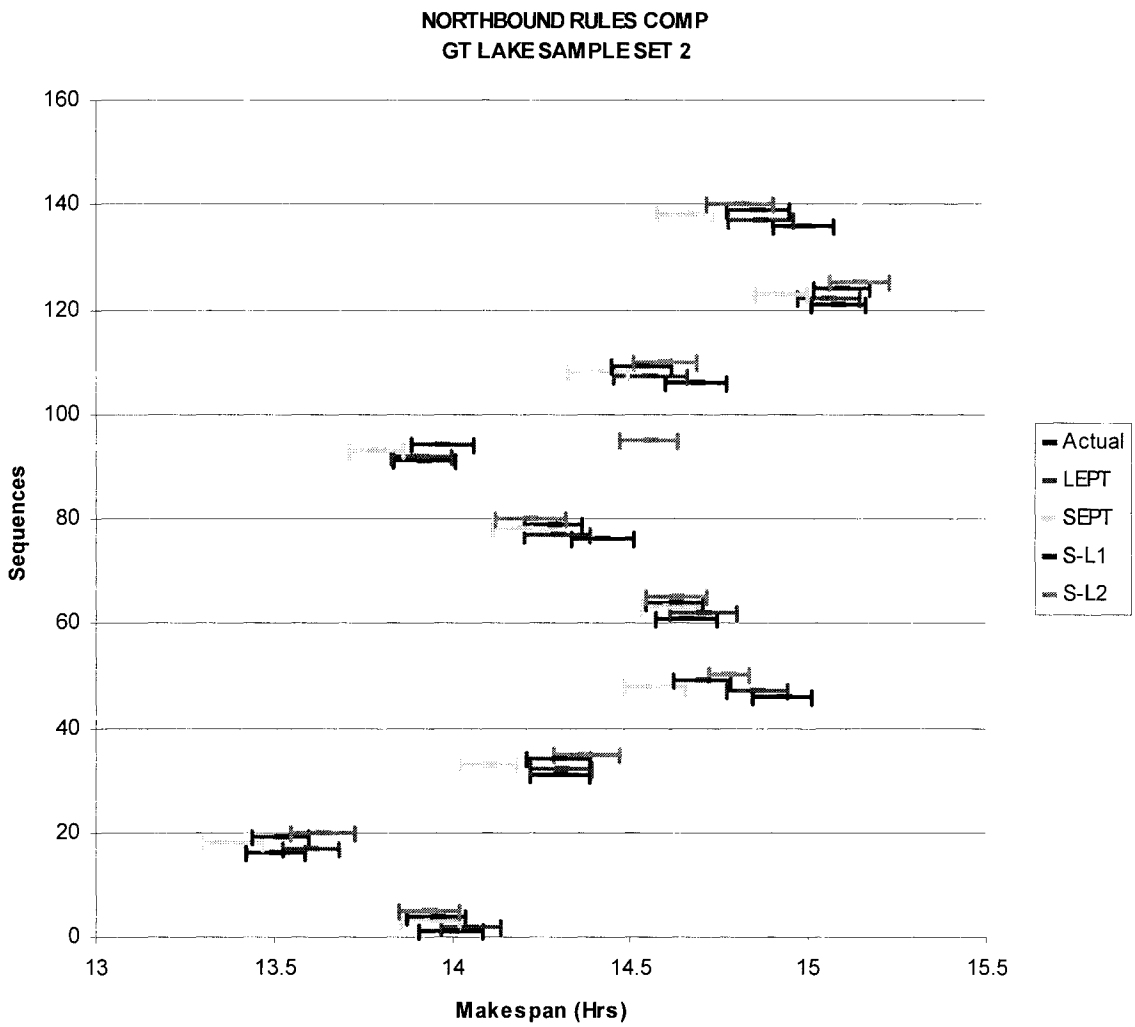

Figure E3 Confidence intervals for Northbound sample set 2 GT Lake. Different Rules Comparison

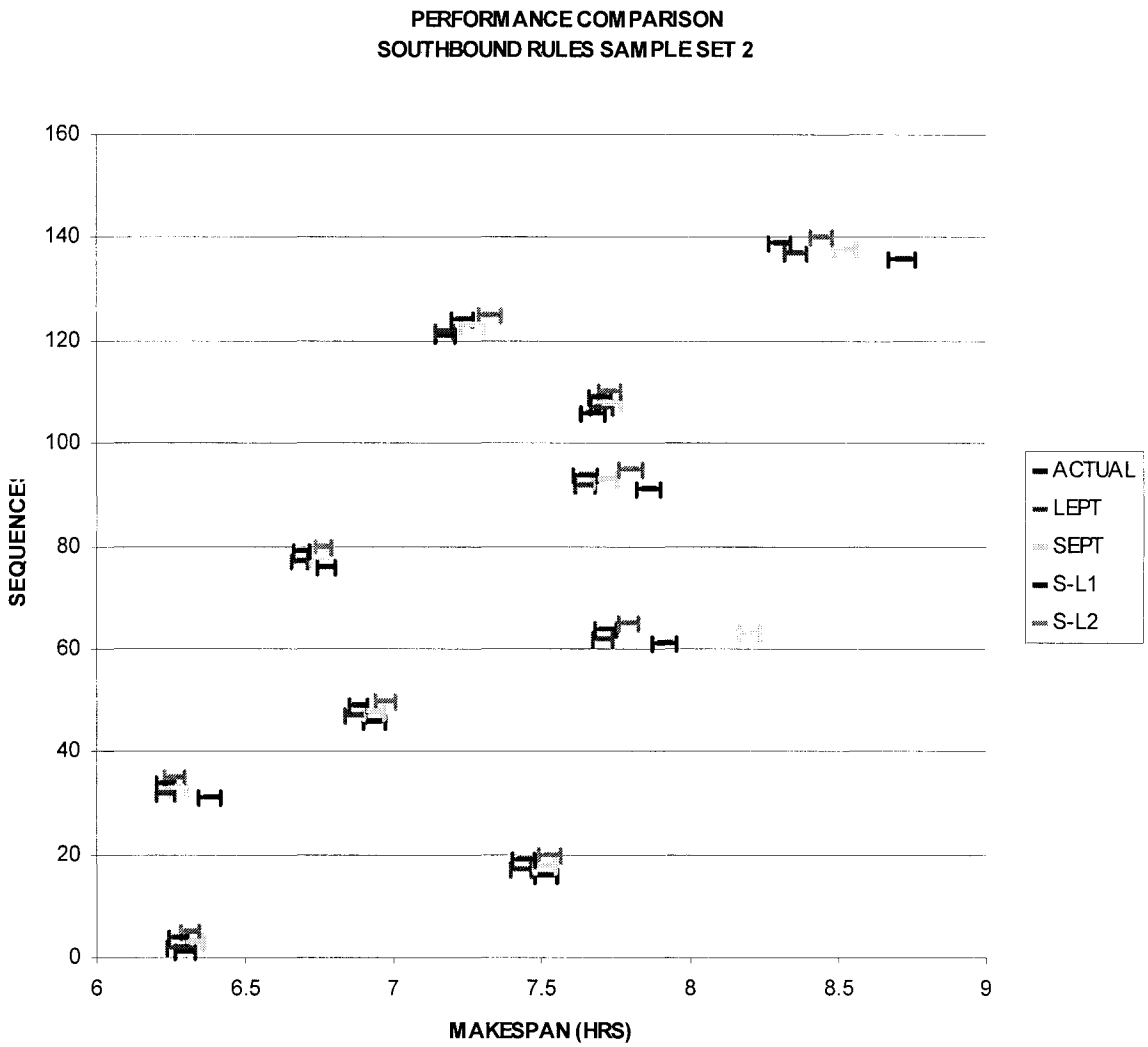

Figure E4 Confidence intervals for Southbound sample set 2 Different Rules Comparison